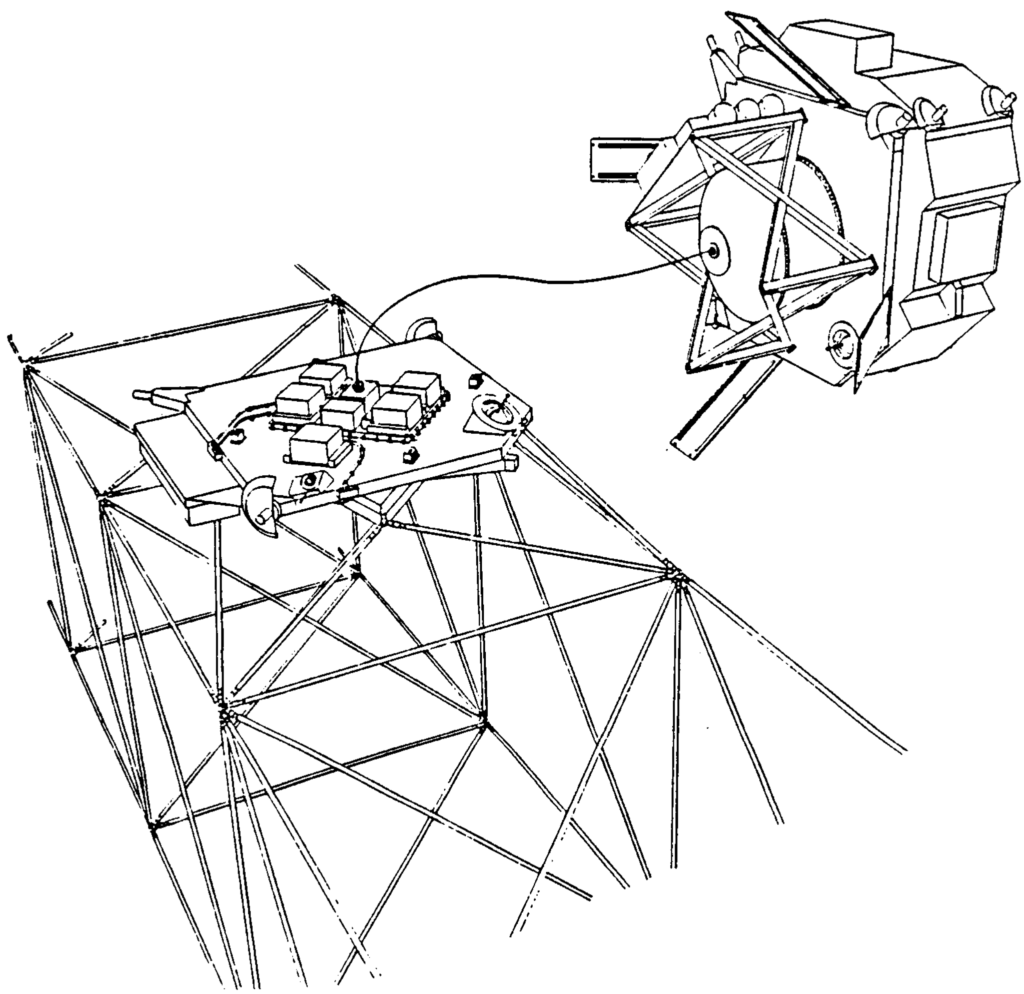
Electrodynamic Tether System Study

Final Report

September 1987
Contract : NAS9-17666



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Acronyms

AC	Alternating Current
AKA	Active Keel Actuator
AO	Atomic Oxygen
AWG	American Wire Gauge
BASD	Ball Aerospace Systems Division
CG	Center of Gravity
C&DH	Command and Data Handling
CRRES	Combined Radiation Release Effects Satellite
DC	Direct Current
DCA	Deployed Carrier Assembly
DDIS	Deck-to-Deck Interface Structure
DMS	Data Management System
EFGF	Electrical Flight Graph Fixture
EMC	Electro Magnetic Cleanliness
EMI	Electro Magnetic Interference
EPS	Electrical Power System
ETS	Electrodynamic Tether System
EVA	Extra-vehicular Activity
FCA	Fixed Carrier Assembly
FSE	Flight Support Equipment
FSS	Flight Support System
GFE	Government Furnished Equipment
GTOSS	Generalized Tethered Object Simulation System
HVDC	High Voltage Direct Current
ICA	Integrated Carrier Assembly
IGRF	International Geophysical Reference Field
IOC	Initial Operations Configuration
JSC	Johnson Space Center
LRM	Line Replaceable Module
LVAC	Low Voltage Alternating Current
MBSA	Main Bus Switching Assembly
MLI	Multi-layer Insulation
MMS	Multi Mission Satellite
MRMS	Mobile Remote Manipulator System
NASA	National Aeronautics and Space Administration

OD	Outside Diameter
OMV	Orbital Maneuvering Vehicle
PDCA	Power Distribution and Control Assembly
PMAD	Power Management and Distribution
PMC	Power Management Controller
PMG	Plasma Motor Generator
PRLA	Payload Retention Latch Actuator
PSC	Power Source Controller
PV	Photovoltaic
RBI	Remote Bus Isolator
RMS	Remote Manipulator System
SD	Solar Dynamic
SDP	Standard Data Processor
SIA	Station Interface Adaptor
SS	Space Station
SSM	Space Service Module
STS	Shuttle Transportation System
SURS	Shuttle Umbilical Release System
TRACE	Trajectory Analysis Program
TSAT	Tethered Satellite Project

1.0 INTRODUCTION

This report covers the results from the Electrodynamic Tether System (ETS) Study through August 1987. The purpose of this program is to define an ETS that could be erected from the Space Station and/or Platforms to function as an energy storage device. Excess output from the SS or Platform solar power systems would be directed into the tether during the daylight portion of orbits. This would result in increasing the energy of the orbit (motor mode). During the earth eclipse periods energy would be drawn from the tether (generator mode) to replace the lost output of the solar power systems. In effect the tether would replace or augment the usual battery storage facilities. This is often referred to as a Plasma Motor Generator (PMG) system in the literature.

The basic configuration of an ETS consists of a conducting tether, a device for regulating the flow of energy into and out of the tether, and a device to provide an electrical contact to the space plasma. A reference system consisting of a 20 km tether sized to deliver 200 kW was used as a starting point to define the mechanical and electrical configuration. The device that provides the contact with the space plasma was assumed to be a Hollow Cathode Plasma Contactor. These devices have the advantages of allowing bi-directional flow of current and small power and size requirements.

The design arrived at is presented in the following report. The system is modular and allows for orbital maintenance and repair using robotic and/or EVA procedures. The system is sized at 100 kW for initial operations due to solid state component constraints. However, a growth path to 200 kW and larger systems is provided by using improved components and/or parallel arrangements of the basic design.

Figure 1.0-1 is a schematic representation of the ETS concept mounted on the Space Station. The system is launched in the Space Shuttle as two separate Integrated Carrier Assemblies (ICA). One ICA is placed on the upper SS boom and one on the lower SS boom. Each of the ICA's are made up of two pieces, a fixed and a removable piece. The fixed piece is referred to as the Fixed Carrier Assembly (FCA) and the removable piece as the Deployed Carrier Assembly (DCA). However, the FCA is attached to the DCA by a 10 km insulated aluminum tether which is the conductor the current flows through. The DCA is deployed using the Orbital Maneuvering Vehicle (OMV) for control, since no reeling mechanism is used. One of the DCAs is deployed upward 10 km and one downward 10 km.

Current and voltage control for the ETS is provided by eight bi-directional converter modules that interface through the SS Power Management and Distribution (PMAD) system. The converters use designs and components that are common with the SS power system.

In addition to the hardware design and configuration efforts, the report also documents studies involving simulations of the Earth's magnetic field and the effects this has on overall system efficiency calculations. It also discusses some preliminary computer simulations of orbit perturbations caused by the cyclic day/night operations of the ETS.

The final sections of the report provide system cost estimates, an outline for future development testing for the ETS system, and conclusions and recommendations from this study.

2.0 STUDY DEFINITION

The Plasma Motor Generator (PMG) system described by Dr. McCoy of NASA JSC[1] was used as the starting point for this study effort. This reference system consists of a 20 km tether (10 up and 10 down) constructed of #00 AWG aluminum wire with teflon insulation. The conductor diameter is 9.3 mm and the total diameter of the tether, including the insulation, is 10.3 mm. The system has a rated power of 200 kW (25 N thrust) with a peak power of 500 kW for contingency operations. This system is sized for Space Station (SS) power levels, but is suitable for many other applications including free-flying platforms.

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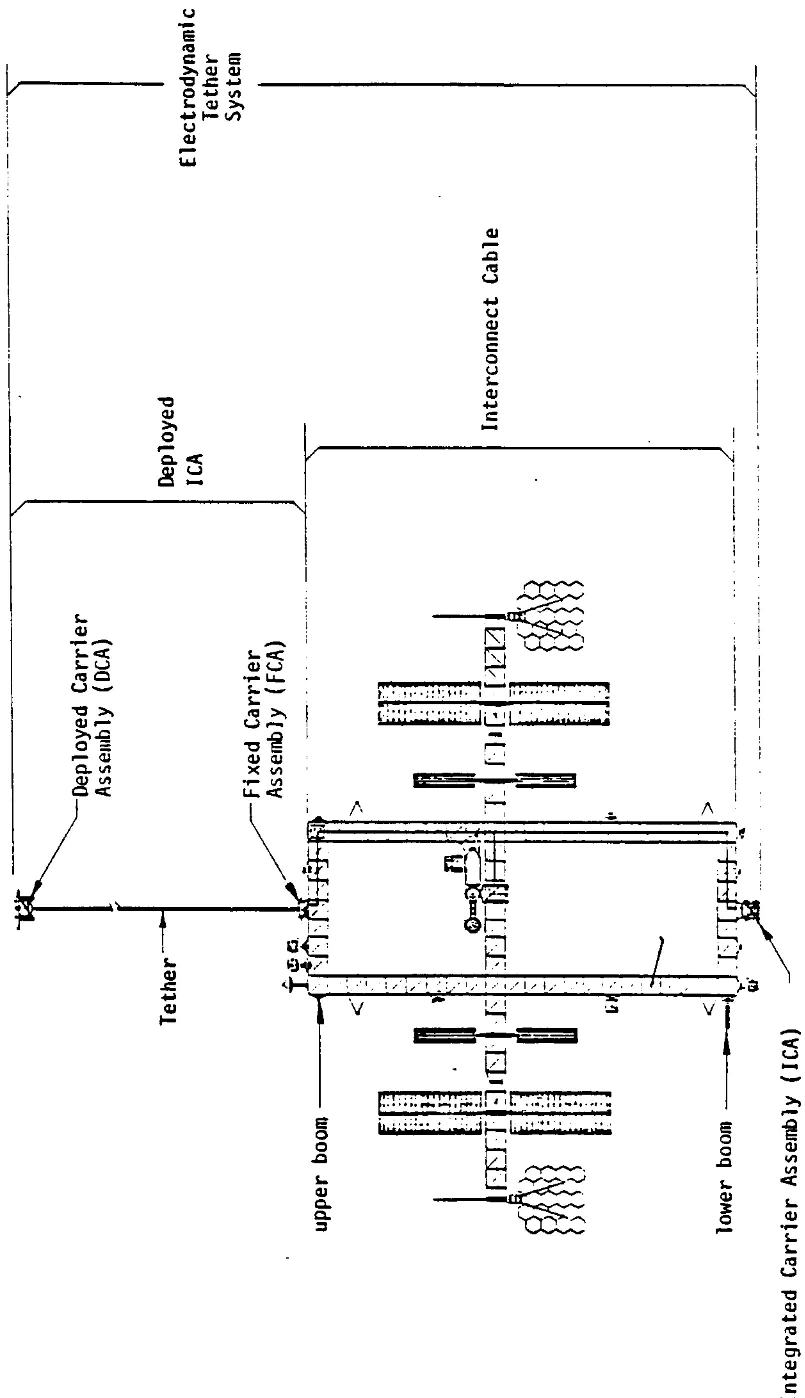

Figure 1.0-1 Electrodynamic Tether System Concept

Using this reference system as a starting point the major goals of this study were as follows:

- Define the structure of the power conversion electronics required to interface the electrodynamic tether to a Space Station type electrical system
- Establish a configuration for the electrodynamic tether system given that a hollow cathode plasma contactor will be used as the interface to the space plasma
- Investigate the key development and cost drivers associated with a PMG type electrodynamic tether system
- Perform parametric studies to determine if the 200 kW tether design is a cost effective system and what are the major design trades are for this type of system
- Examine the impact, if any, of using IxB phasing to control tether librations
- Define an operational scenario for the system
- Examine the safety implications of employing an electrodynamic tether including identifying procedures applicable to a severed tether situation
- Define the technology necessary to implement the electrodynamic tether conversion system and identify those areas needing further development
- Outline a test program that will make use of ground facilities and ,if required, a flight demonstration program to address those areas of the tether concept that need testing for proof of concept
- Provide a preliminary cost estimate for the design, development, build and test of the electrodynamic tether system

The operation of the hollow cathode plasma contactor was not analyzed in this study. Its operating parameters were taken from published test data[2] and interim reports[3] of ongoing development of these devices. The tether current levels required for this study are in excess of those verified by test, so the performance has been extrapolated. The electronics necessary to control the contactors were also assumed to be supplied and are not discussed in detail.

3.0 SYSTEM MECHANIZATION

3.1 Power Converter Design

The design drivers for the power converters are maximum voltage, maximum current, maximum voltage swing, bi-directional operation, and the Space Station Power Management and Distribution (PMAD) interface requirements. Therefore, before the converter design could proceed each of these items had to be quantified or at least bracketed. In the following sections the induced voltage variations, in terms of the magnetic field variation at SS orbits, will be discussed and a brief description of the IOC SS power system architecture will be presented. This will be followed by a detailed description of the converter design, operation, and packaging.

Magnetic Field Model

A study of the Earth's magnetic field properties at 500 km was undertaken to determine what effects might be expected in an electrodynamic tether from variations in the field. The results of this study are needed in the design and specification of the power converters, developing mission operations scenarios, and evaluation of the IxB phasing for tether libration control. It was also believed that the results would be beneficial in determining the best models to use in electrodynamic tether simulations using simulation programs such as GTOSS.

The study compared a variety of mathematical models of the Earth's magnetic field with respect to variations in magnitude and direction, both of which are important to analysis of these type of systems. The models considered in the study were the tilted dipole and the International Geomagnetic Reference Field (IGRF) with epoch 1985 coefficients. The dipole models used included the GTOSS (subroutine GAUSS) model and the dipole resulting from using the first coefficient of the IGRF spherical harmonic expansion. The full tenth order IGRF model was used as the reference field for comparison purposes. The IGRF was chosen as the reference because it is widely accepted and used throughout the world.[4]

Figure 3.1-1 is a plot of magnetic field intensity contours at 500 kilometers for the IGRF reference model on a map of the Earth. Figure 3.1-2 is the same type of plot for the IGRF tilted dipole model (1 term) and Figure 3.1-3 is a plot of the difference in magnitude between the two field models (all in gauss). Note that significant variations in the field magnitude take place within +/- 40 degrees latitude of the equator.

The variation in the field magnitude at Space Station altitude (500 km) and inclination (28.5 degrees) is of particular interest for the electrodynamic tether study. Figure 3.1-4 is a plot of the variation in field intensity during several orbits at 500 km and 28 degree inclination. Time zero on the plots corresponds to zero degrees longitude and latitude. The field intensity for the full 10th order IGRF field and the 1 term dipole model are plotted. Note that this dipole model predicts maximum field intensities considerably less than the full IGRF model. However, the minimum values and phasing are predicted with better accuracy.

Figure 3.1-5 shows the variation of magnetic field intensity predicted by the GTOSS shifted and tilted dipole model (subroutine GAUSS of version C3) compared to the full IGRF model. Note that for this model the maximum values for the dipole are significantly higher than the full IGRF and, again, the minimum values are fairly consistent. Figure 3.1-6 plots the ratio of the magnetic dipole models (GTOSS and IGRF 1 term) and the full IGRF model.

It should be noted that the GTOSS model predicts field intensities consistently higher than the true field while the IGRF single term dipole predicts intensities slightly lower than the true field values. Another important parameter of the magnetic field model is the direction of the field. A comparison of the field direction of the dipole model versus the IGRF 10th order model was completed as part of this study. Figure 3.1-7 shows a contour plot of the angle between the dipole magnetic field vector and the IGRF field vector. The dipole model used for these plots

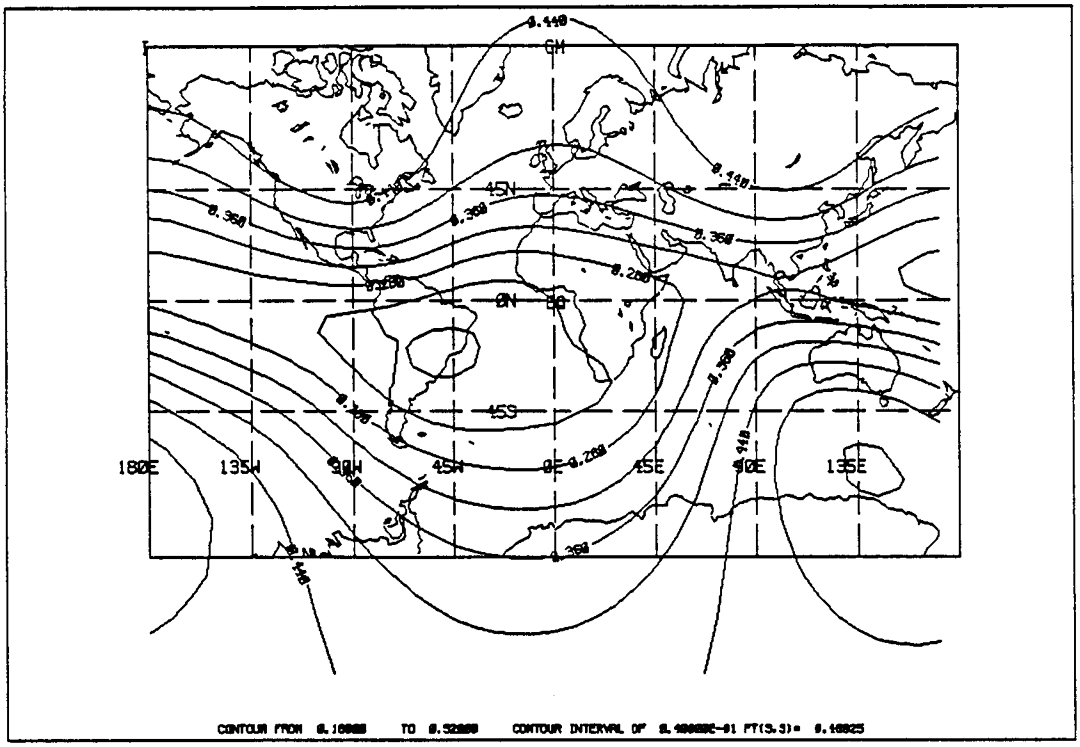

Figure 3.1-1 IGRF Magnetic Field Intensity (Gauss)

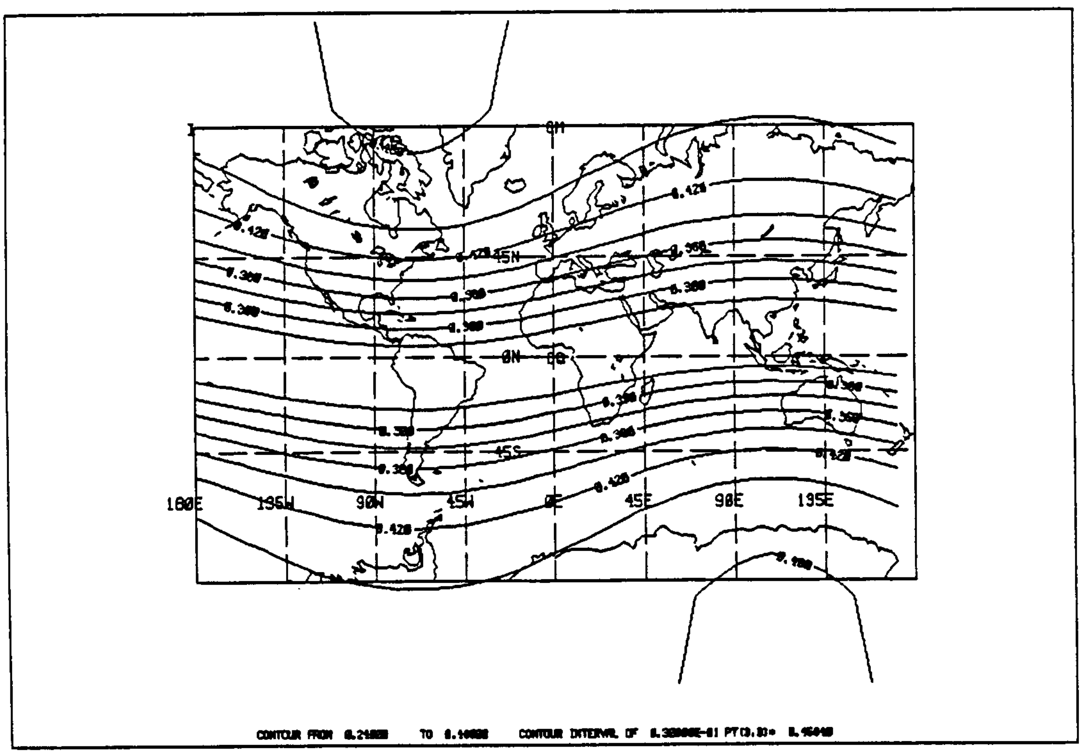

Figure 3.1-2 Tilted Dipole Mag. Field Intensity (Gauss)

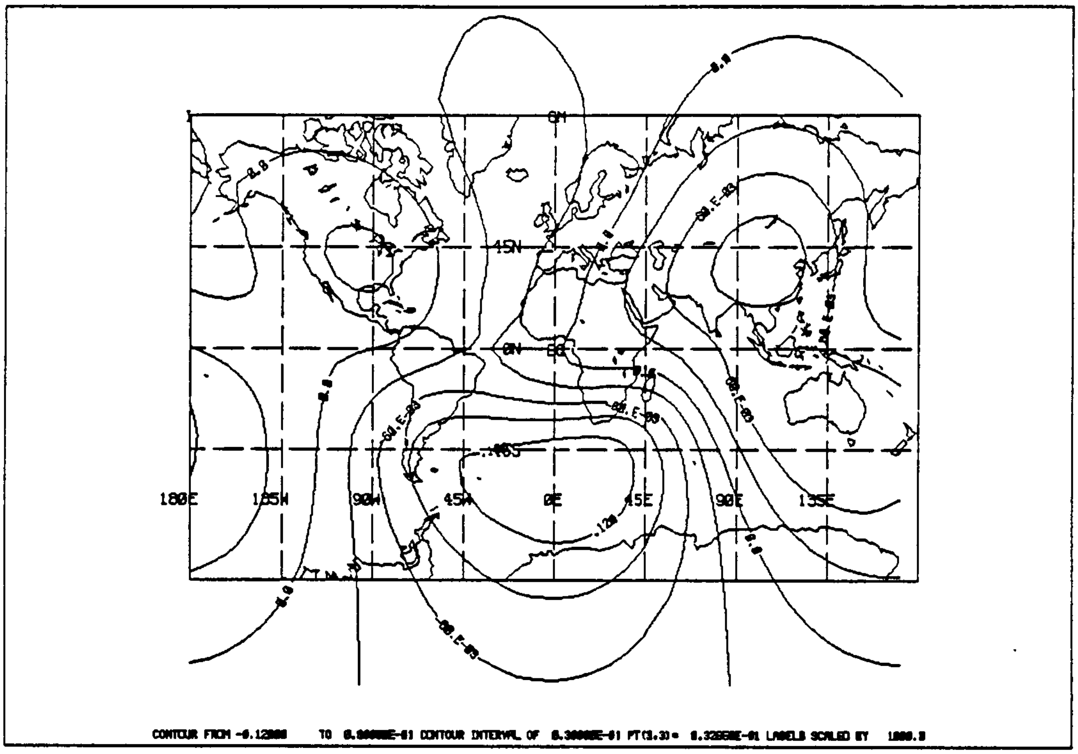

Figure 3.1-3 Difference Between IGRF & Dipole Intensities

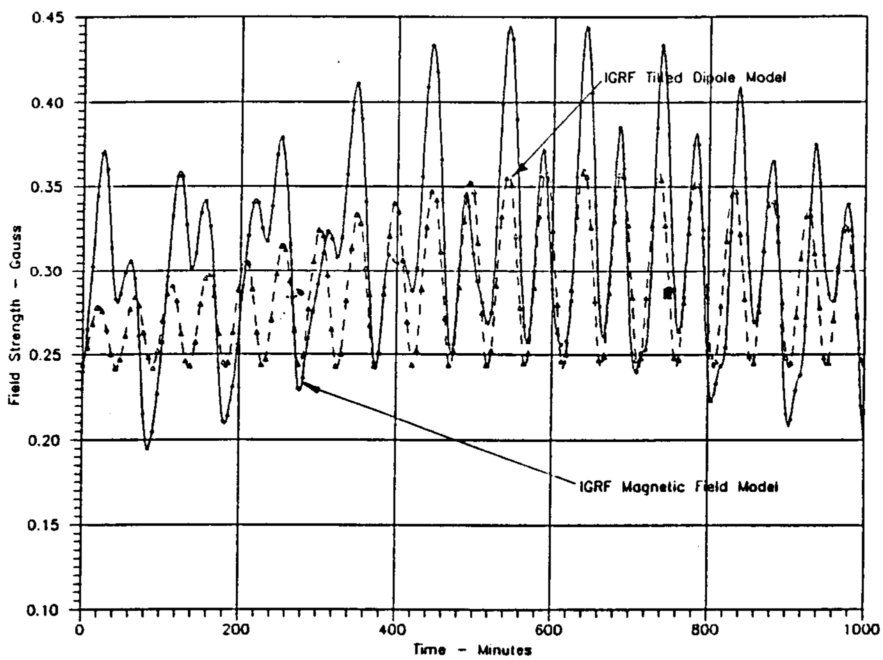

Figure 3.1-4 Field Strength At Space Station Orbit

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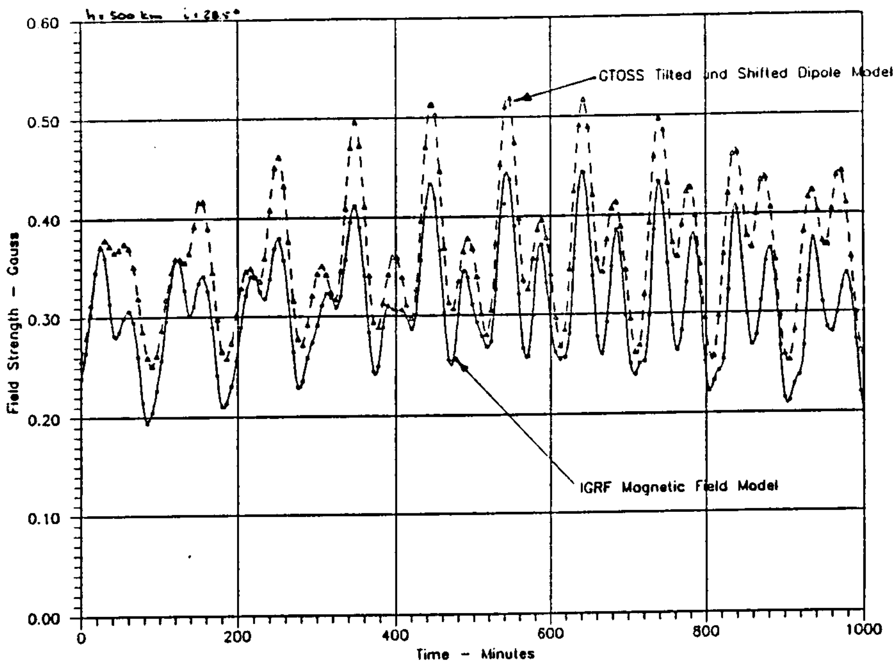

Figure 3.1-5 IGRF vs GTOSS Magnetic Field Strength

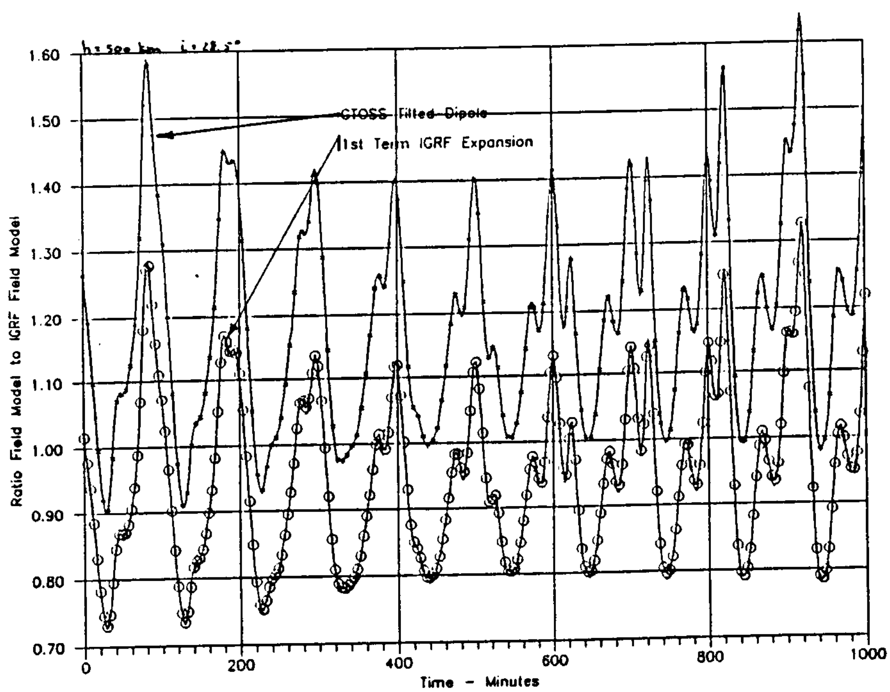

Figure 3.1-6 Ratio of Dipole Fields to IGRF Field

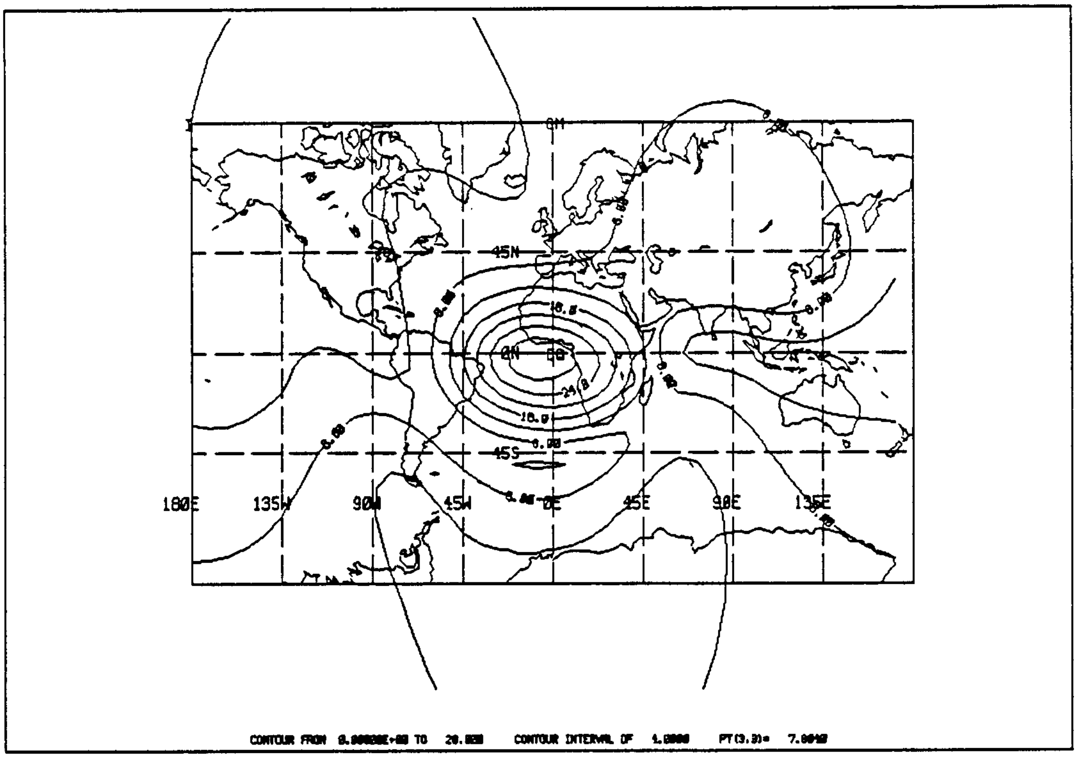

Figure 3.1-7 Differences In Magnetic Field Direction

was the single term IGRF model. The variation can be greater than 30 degrees for areas over the South Atlantic.

Figure 3.1-8 shows the variation for the models evaluated in this study during typical Space Station orbits. This figure is instructive in that all of the models have almost exactly the same deviation from the IGRF 10th order model. The next several figures examine the origin of this difference in direction by comparing the elevation and azimuth components of the field vectors.

Figures 3.1-9 and 3.1-10 are plots of the field elevation angle at various points on the Earth. An elevation angle is relative to the local horizontal with zero indicating a vector in the local horizontal plane. Figure 3.1-9 is the data for the IGRF 10th order field and Figure 3.1-10 is for the tilted dipole (IGRF single term). The elevation difference between these two models is plotted in Figure 3.1-11. The elevation component is 30 degrees or more in the South Atlantic region. Figures 3.1-12 and 3.1-13 show similar data for the azimuth angle (relative to spin axis North) of the field models.

The impact of the magnitude and direction variations of the magnetic field on the predicted voltage in a 20 kilometer long tether are illustrated in Figure 3.1-14. This is a plot of the voltage induced in a straight tether oriented along the local vertical at 500 km and a 28 degree inclination. The two tilted dipole models do not accurately predict the voltage swings encountered on a single orbit. The GTOSS shifted and tilted dipole model does a good job of simulating the voltage swings except the magnitude of the voltage is too high. This gives an apparent orbital variation of 4900 to 2850 volts (a 1.72 to 1 variation) over a typical day. The IGRF 10th order model predicts a voltage variation of 4000 volts to 1300 volts (a 3.07 to 1 variation) over the same period. These predicted values agree very well with a similar analysis completed by MIT.[5] This is a very important difference for power conversion equipment design.

This study did not include the effects of libration on the induced voltages. This could be quite significant, especially in the South Atlantic region where the direction of the magnetic field

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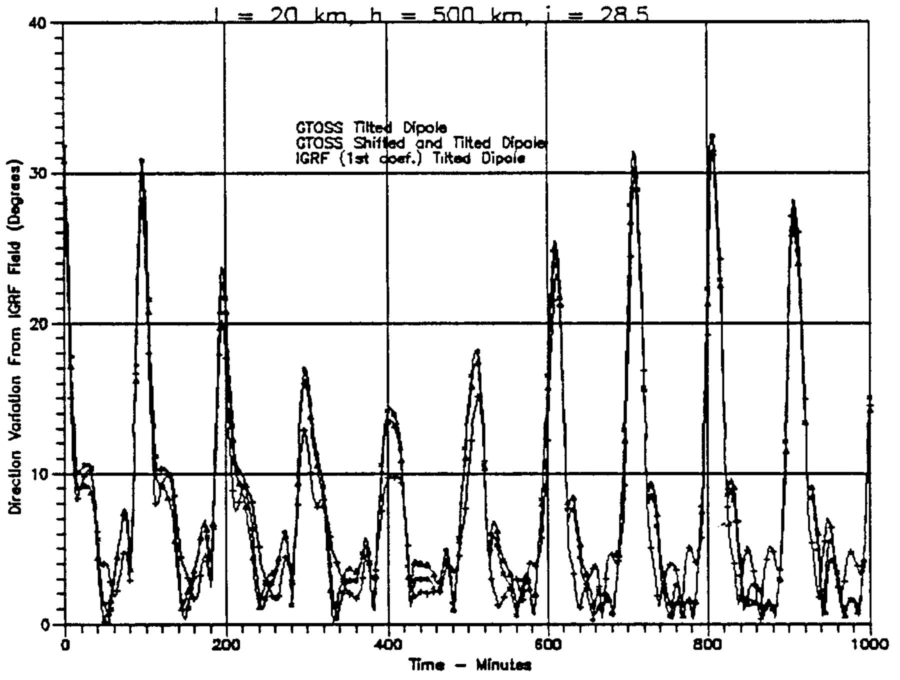

Figure 3.1-8 Direction Variation From IGRF Field

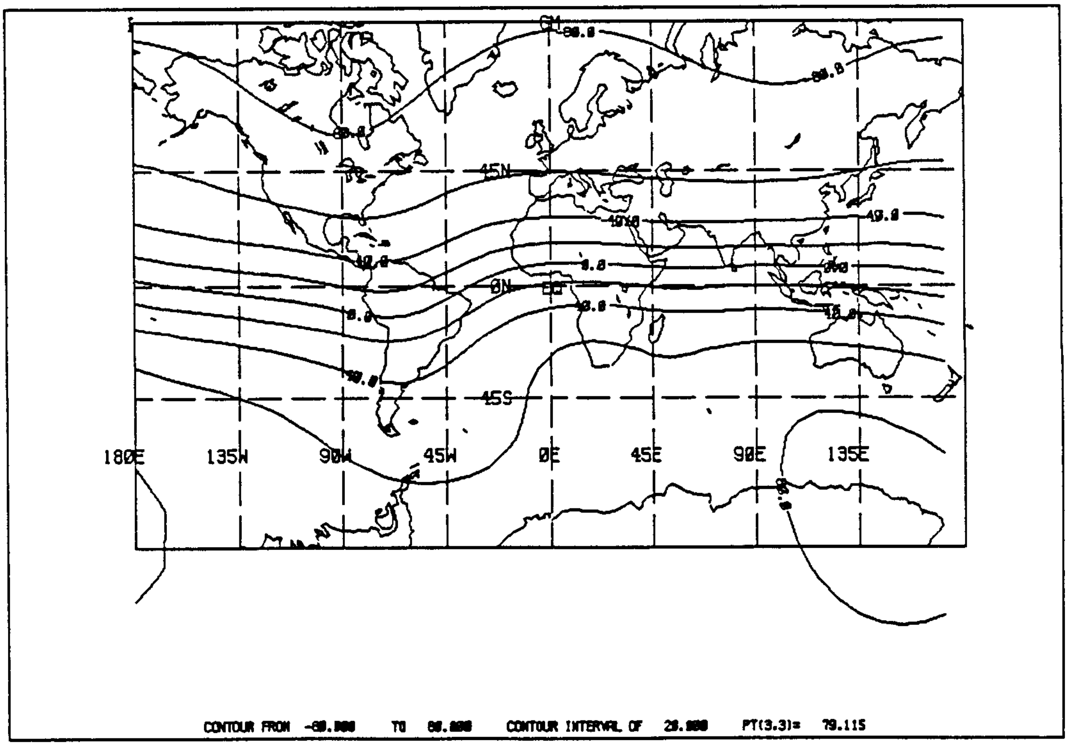

Figure 3.1-9 Elevation Angle of IGRF Field Vector

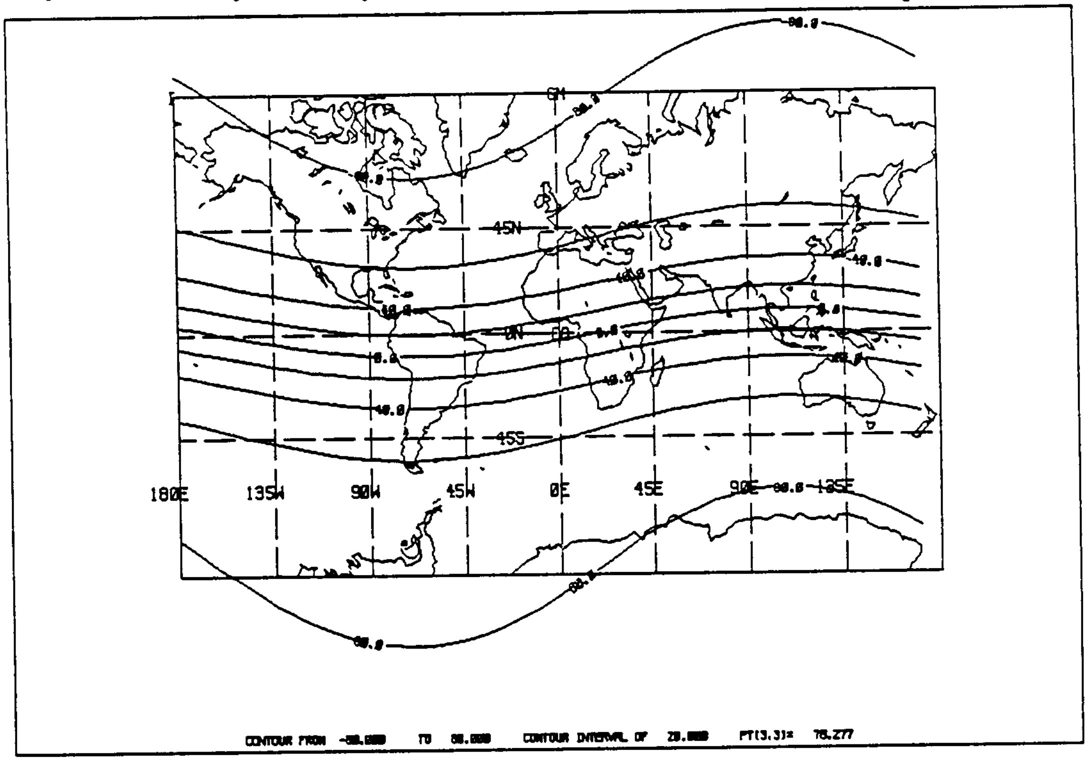

Figure 3.1-10 Elevation Angle of Tilted Dipole Field Vector

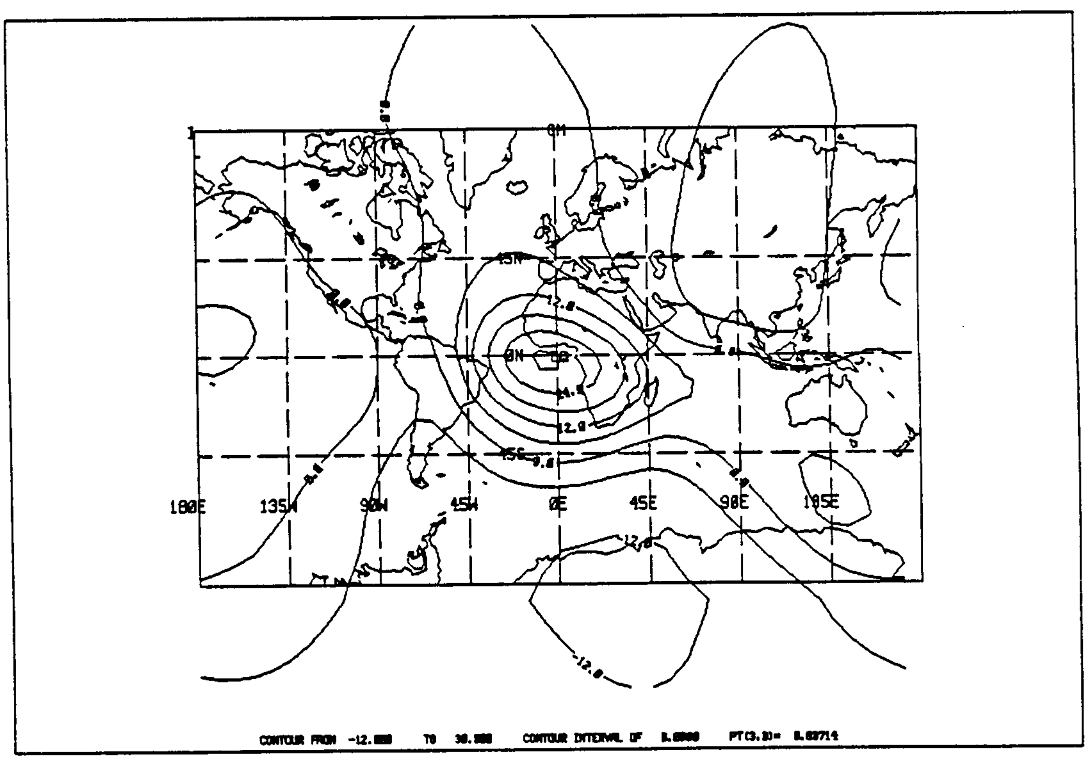

Figure 3.1-11 Difference In Elevation Angle- IGRF vs Diploe

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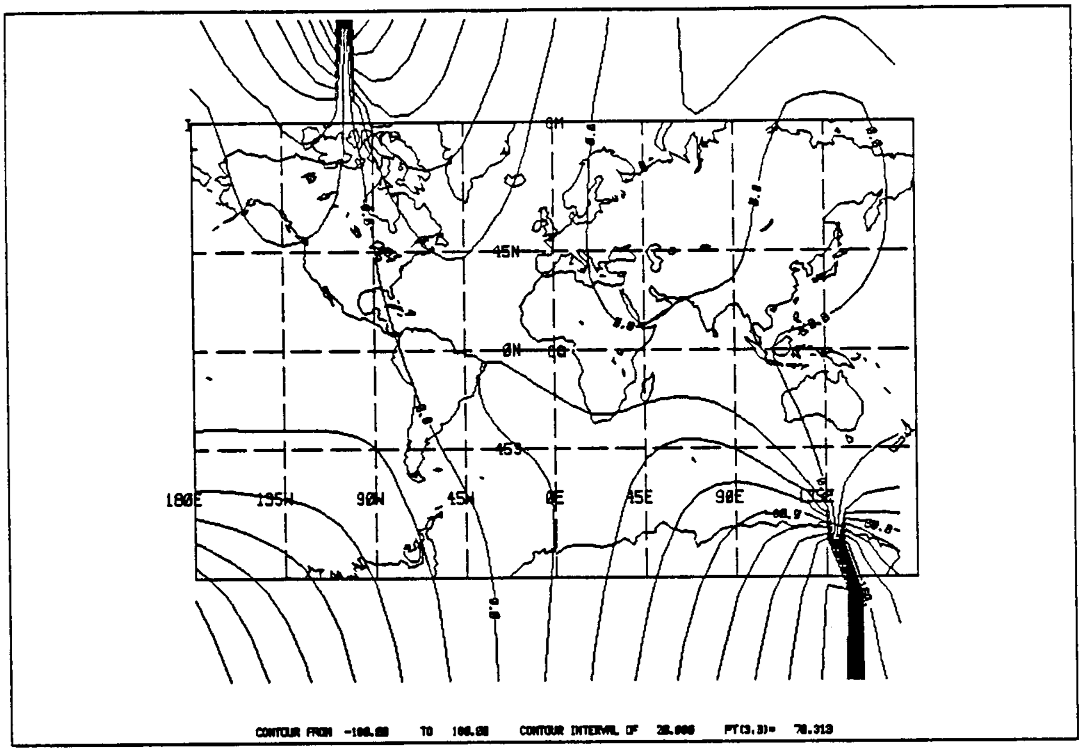


Figure 3.1-12 Azimuth Angle of IGRF Field Vector

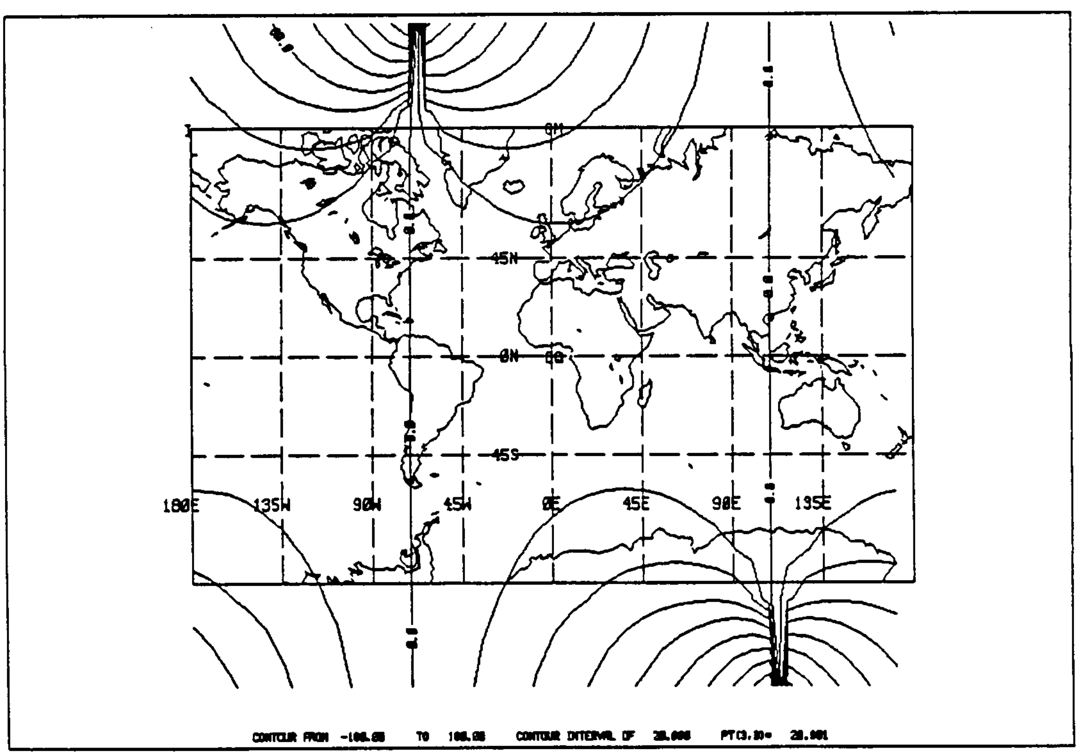


Figure 3.1-13 Azimuth Angle of Tilted Dipole Field Vector

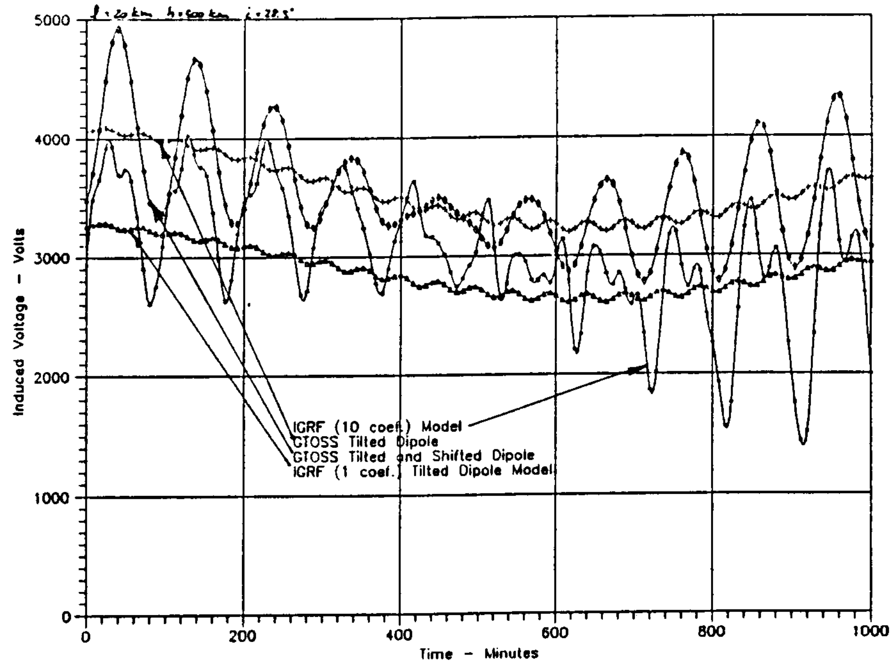


Figure 3.1-14 ET Induced Voltage at Space Station Orbit

vector varies so radically. It appears from this study that tether simulations that include electrodynamic effects should consider the choice of magnetic field model very carefully. This is especially true evaluating tether librations and determining IxB phasing needed to obtain levels within acceptable limits. Sizing of electrical components for tether current control should use the dynamic range for voltage predicted by at least a shifted and tilted dipole model if the full IGRF model is not available.

Space Station Electrical Power System (EPS)

The Space Station PMAD system will be used to monitor and control the Electrodynamic Tether System (ETS) converters. The current design for the SS system[6] uses a hierarchical set of interconnected computers which coordinate, manage and control operation of the power system. Overall coordination is accomplished by a set (one in-board of each alpha joint) of Power Management Controllers (PMC) which are constructed from Data Management System (DMS) Standard Data Processors (SDP) designed for common use throughout the SS constellation. The data processors interface to other subsystems through the DMS global data network.

A dedicated, dual redundant, power management control bus is used to interface between the PMC and other elements of the power subsystem. This control bus is distinct from the DMS global network and logically connects the Power Source Controller (PSC) outboard of the alpha joints and the Main Bus Switching Assemblies (MBSA) plus the Power Distribution and Control Assemblies (PDCA) inboard of the alpha joint. Figure 3.1-15 illustrates the proposed architecture for the SS dual keel configuration.

The SS main power bus will be a 440 volt 20 kHz AC system. The ETS converters will be synchronized to this system by the SS power controllers. Primary control of the converters will be accomplished by PSC's located on the upper and lower keels. The PSC will synchronize the converters with the output of the other SS power sources and control the mode of opera-

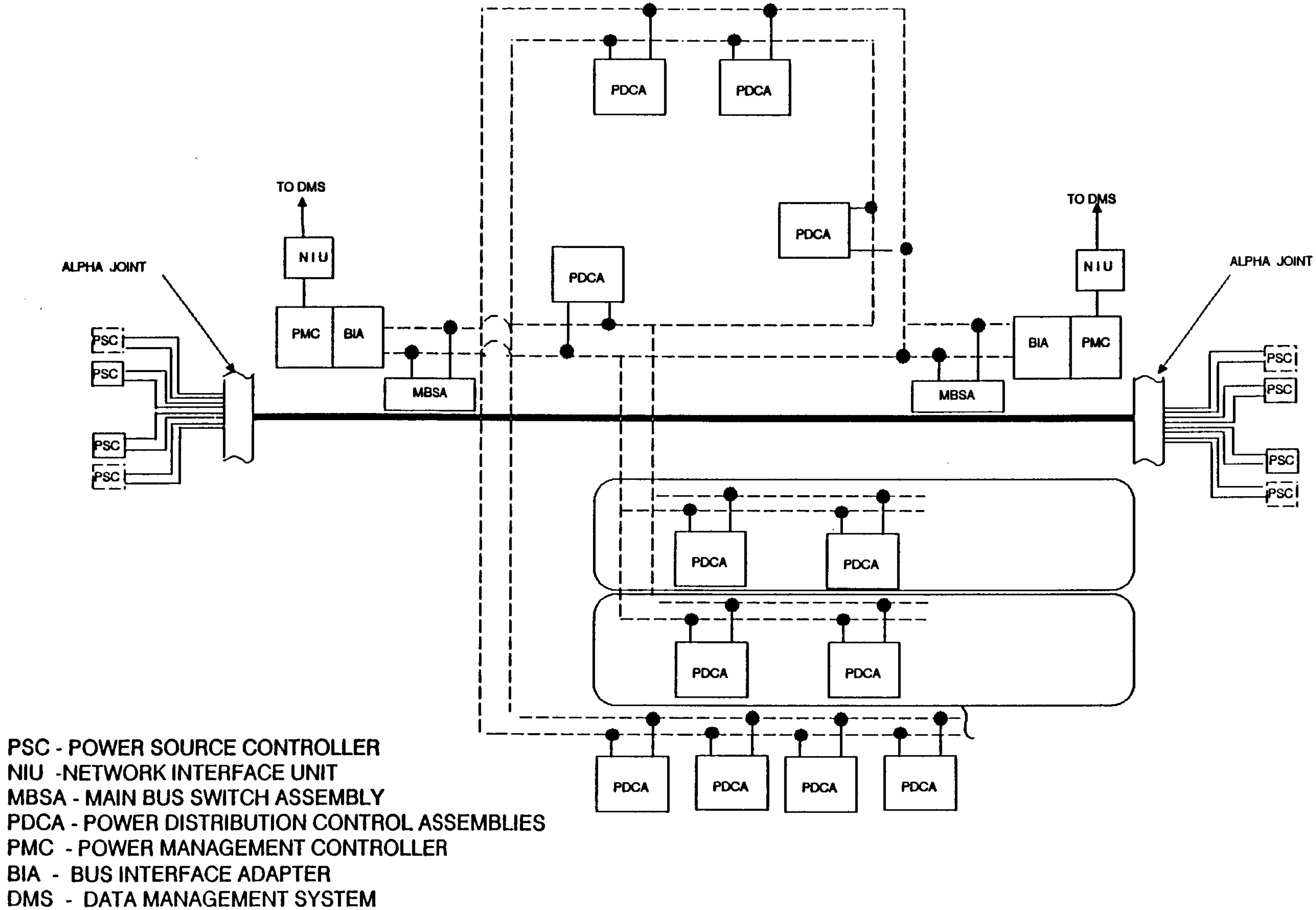


Figure 3.1-15 Power Management Architecture - Dual Keel

tion (i.e. motor or generator) for the ETS. The PSC's will also control the Remote Bus Isolators (RBI) that are used to isolate and diagnose failures in the ETS converters.

The ETS converters interface to the SS main power bus through the PMAD main inverters, which also are under the control of the PSC. The high power level of the ETS will require dedicated PSC's and PMAD inverters. These components will be in addition to similar components used for the Photovoltaic (PV) and Solar Dynamic (SD) power systems.

Converter Theory of Operation

Motor and generator modes of operation for the ETS will be processed and regulated by the PMAD computer control system in the same manner that power is taken from solar, fuel cells, etc., or power returned to batteries or thermal storage. The station PMAD system will accept AC or DC power from any available source, as well as provide regulated AC or DC as required for various loads.[7] At the present state of development, it appears that 25 - 30 kW converter modules are to be used in the PMAD system.

Since the tether can be used either as a generator or a motor, a bi-directional converter capable of controlling current in to or out of the tether must be employed.

In addition to being bi-directional, the converter must operate at relatively high voltage direct current (HVDC) on the tether side, while operating at a relatively low voltage alternating current (LVAC) on the station side to be directly compatible with the station PMAD system.

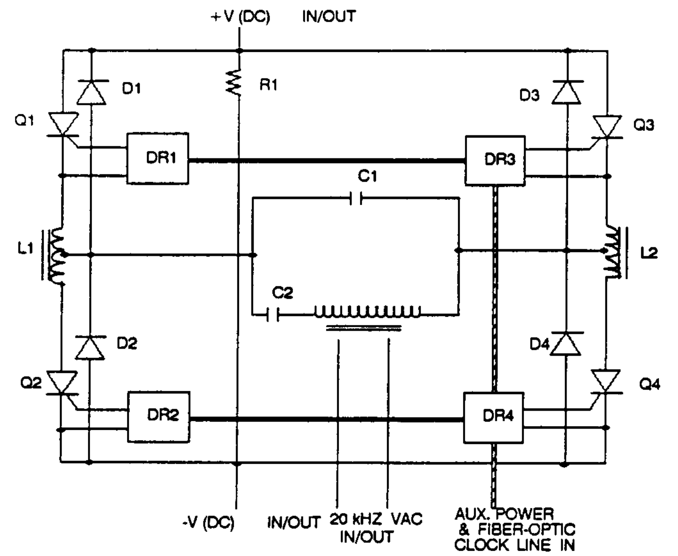
Early in this investigation, a number of DC/DC conversion schemes were evaluated, (DC to batteries or thermal storage, for example) however, it was found that considerable additional complexity and loss of efficiency would result from these approaches.

Reviewing the 200 kW reference system of Dr. McCoy we find a nominal tether generator voltage of 4 kV for a 20 km length. In actuality, this will vary from less than 1.5 kV to 5 kV depending on orbital conditions and tether orientation. A constant 200kW output under these conditions requires current levels between 133A and 40A. This current level could be achieved by paralleling devices, but this would complicate the control and synchronization of the converters. Therefore, a more conservative power level of 100 kW was selected to be consistent with components available in the near future. This power level can be easily increased as component technology improves. In addition we have limited the full load range of operation to between 2.5 kV and 5 kV on the tether, in order to stay within practical current and voltage ratings of available semiconductor switching devices. At voltages below 2.5 kV the system will be operated at reduced power output.

High voltage on the tether side of the converter precludes the use of a single converter stage. To remain within adequately derated voltage ratings, we will use multiple low voltage (in the 300 to 600 V range) modules stacked in series to accommodate the high tether voltage. The station side of the converter has been well defined by Hansen[8] in his description of the PMAD system and comments relative to current component technology.

To assure compatibility with the PMAD interface, the tether converter circuit topology is identical to that developed at NASA Lewis Research Center. This bi-directional converter topology is based on the original work of Neville Mapham of General Electric in 1967.[9] The basic converter circuit is shown in Figure 3.1-16. Q1 through Q4 are semiconductor switches comprising a bridge drive inverter (DC to AC) and D1 through D4 are rectifiers acting as a full-wave bridge rectifier (AC-DC). The 20kHz tuned circuit is made up of L1 and L2 in series with C1. The input/output transformer T1 connects across C1, with C2 used to maintain flux symmetry in T1.

Operation in the inverter (DC to AC) mode is shown in Figure 3.1-17. This mode is used when the tether is functioning as a generator. The switches Q1 through Q4 are controlled in precise synchronism with the station PMAD system by means of fiber-optic signal links to the



At Full Power:

	Generator Mode	Motor Mode
V (DC) =	312.5 - 625 V	369 V - 660 V
I (DC) =	40 A - 20 A	40 A - 20 A
V (AC) =	220 V - 440 V	260 V - 464 V
I (AC) =	54.5 A - 27.2 A	58.8 A - 29.5 A

Figure 3.1-16 Basic Tether Converter Circuit

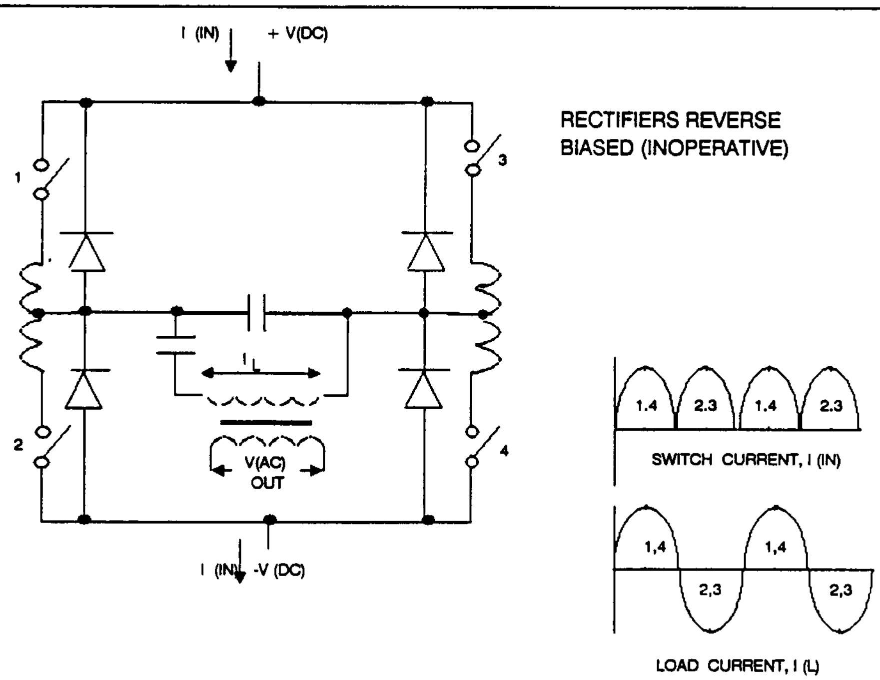


Figure 3.1-17 Inverter Mode, DC to AC, Tether is Generator

switch drivers. This drive method eliminates time delays inherent in long cables and inductive components (transformers), and insures simultaneous switching of all the modules. In this mode, the rectifiers are inoperative, except for possible transient suppression.

When the tether is operating in the motor mode, 20 kHz AC is fed thru T1 and rectified by D1 through D4, with Q1 through Q4 being held off, as shown in Figure 3.1-18. This is the basic bi-directional converter module (or inverter/rectifier) that will be used in the tether/station interface. since this module is identical in topology to the NASA Lewis PMAD converters, it is anticipated that device and component commonalty should exist. Therefore, we plan to use identical switches, rectifiers, resistors, capacitors, drive circuits, etc., as well as NASA standard design practice for the transformer and inductors. This will lead to lower development costs and increased commonality with the SS PMAD system.

The complete converter interface is shown in Figure 3.1-19. CV1 through CV8 are 12.5 kW modules connected in series on the DC (tether side), with the AC (station) side links connected in parallel pairs to appropriate interface PMAD inverters. Space Station standard 60 A distribution cables will be used for the AC links to the PMAD converter modules. With 5 kV maximum on the tether each converter in the series stack sees only 625 V. This voltage across each module is assured not only by equal module loading, but also by the bleeder resistor R1 in Figure 3.1-16. It is proposed that two groups of four modules each be used, one for each tether half (upper and lower), and located on the upper and lower booms respectively.

Efficiency of each module is estimated to be approximately 96% operating in either mode. Size is estimated as approximately 41.9x39.4x24.1 cm (16.5x15.5x9.5 in.) per module.

Weight is approximately 64.6 kg (142.4 lb) per module. Size and weight of the 25kW station

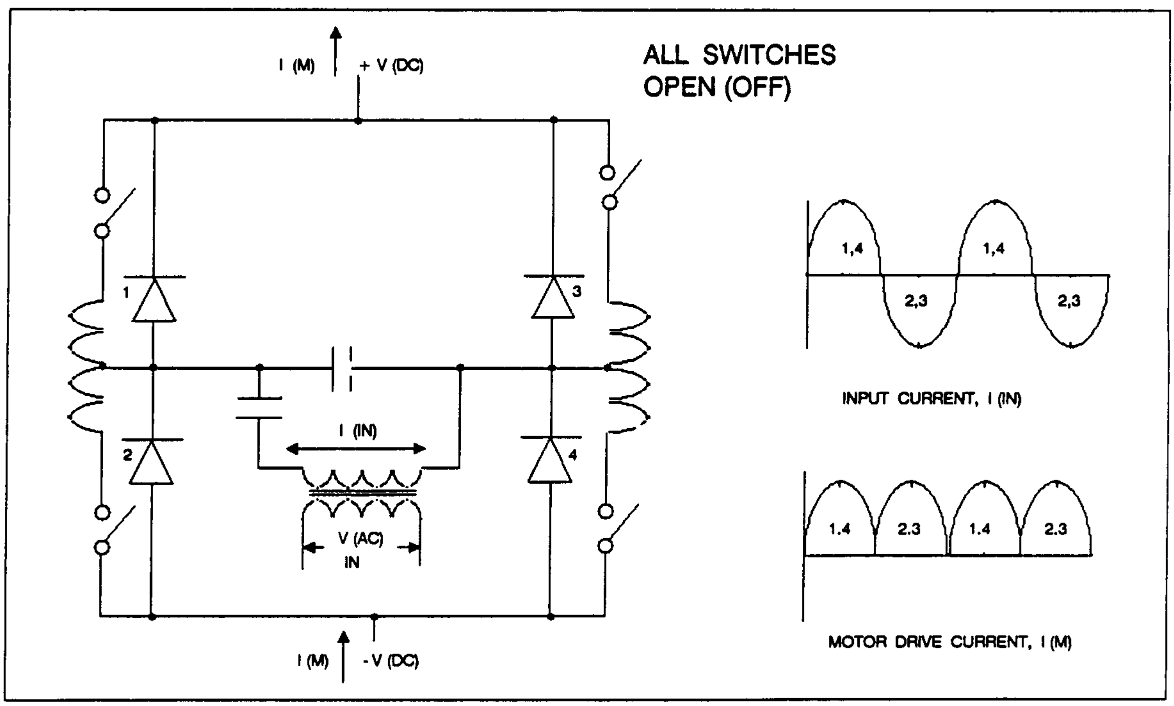


Figure 3.1-18 Rectifier Mode, AC to DC, Tether is Motor

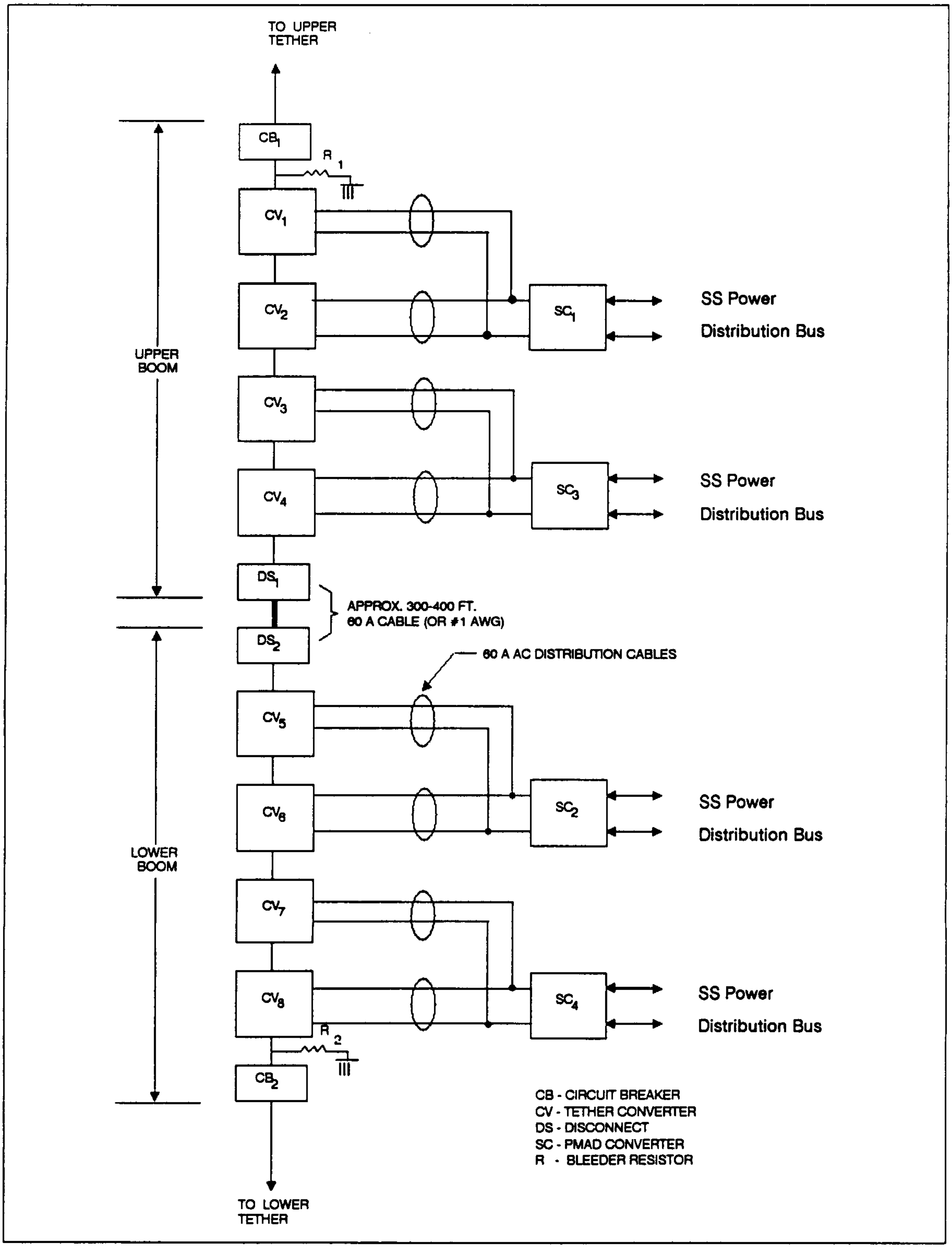


Figure 3.1-19 Tether/Space Station Interface

converter modules are unknown at this time. The converter design is presented in Figure 3.1-20. The major design drivers for the converters were;

- High Voltage
- High Current
- High Power

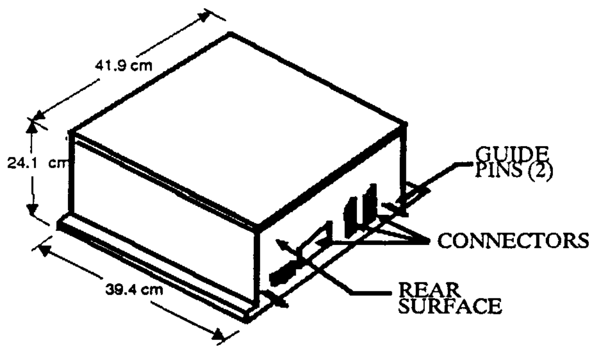


Figure 3.1-20 LRM Configuration

EMI/EMC CONCERNS

EMI/EMC will be a very important subject for Space Station or Platform operation. This subject has not been completely covered with the current design concept because of a lack of some essential data. The effective control of EMI requires that the tether impedance from DC to at least 50 MHz be determined. This impedance must be characterized to allow proper design of any input/output power line filters that may be required.

As part of the tether impedance characterization, a model of the antenna characteristics of the tether must be developed. Since the tether is both a receiving antenna and a transmitting antenna, knowledge of how the tether performs as an antenna is necessary. The antenna characteristics play an important role in keeping power converter signals from interfering with the Space Station and in keeping the Space Station signals from entering the power system.

The Generator mode and the Motor mode of the tether present two distinct noise situations. Each mode must be considered in the EMC design. The following items should be implemented in the EMC design:

- Use differential and common mode filters on the input power lines of the power converter.
- Use differential and common mode filters on the output power lines of the power converters.
- Carefully consider the Printed Wiring Board layout and the interconnect wire routing.
- Keep circuit rise/fall times as slow as possible.
- Use a transformer that minimizes common mode coupling primary to secondary and secondary to primary.

An area of concern is the differential high voltage that will exist between the primary and the secondary of the power converters. This will be as high as 5000 VDC. Because of the high differential voltage, common mode filtering is going to be more difficult. The use of a double chassis should be considered. The primary circuitry would be in one chassis. That chassis would then be inside a second chassis and would include the secondary circuitry.

Finally the tether should be referenced to the Space Station at one point (with respect to DC). A desirable point would be between the two groups of tether converters.

EQUIVALENT TETHER/CONVERTER CIRCUITS

Equivalent tether/converter circuits for both maximum and minimum magnetic fields (in west to east orbit) in both modes of operation are shown in Figure 3.1-21 and Figure 3.1-22. Impedance values for the ionosphere return path, and hollow cathode plasma contactor, were assumed for argument, based on common but not yet proven estimates. The tether and converter voltage sources are represented by the conventional battery symbol, and are considered to

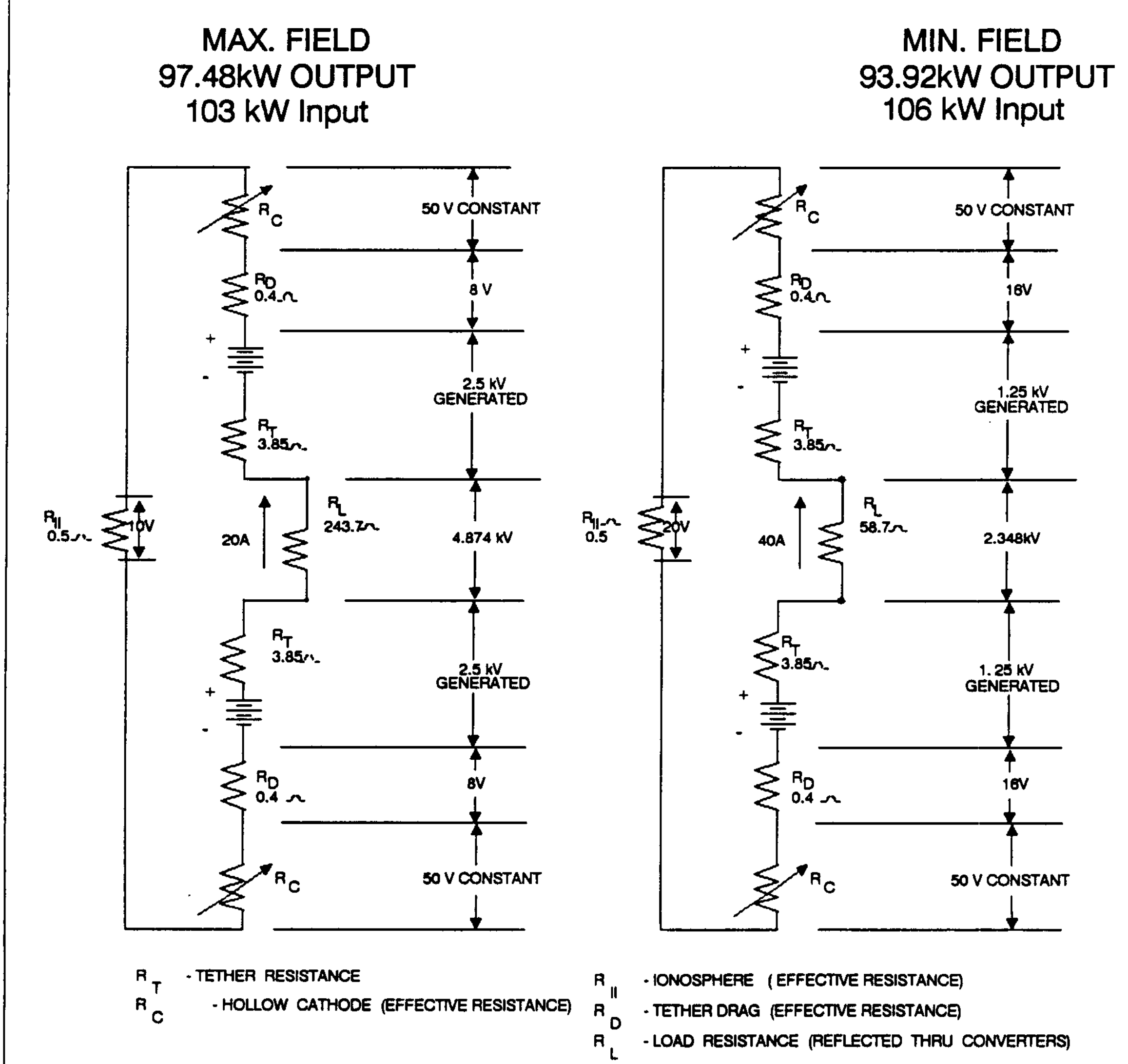


Figure 3.1-21 Tether In Generator Mode

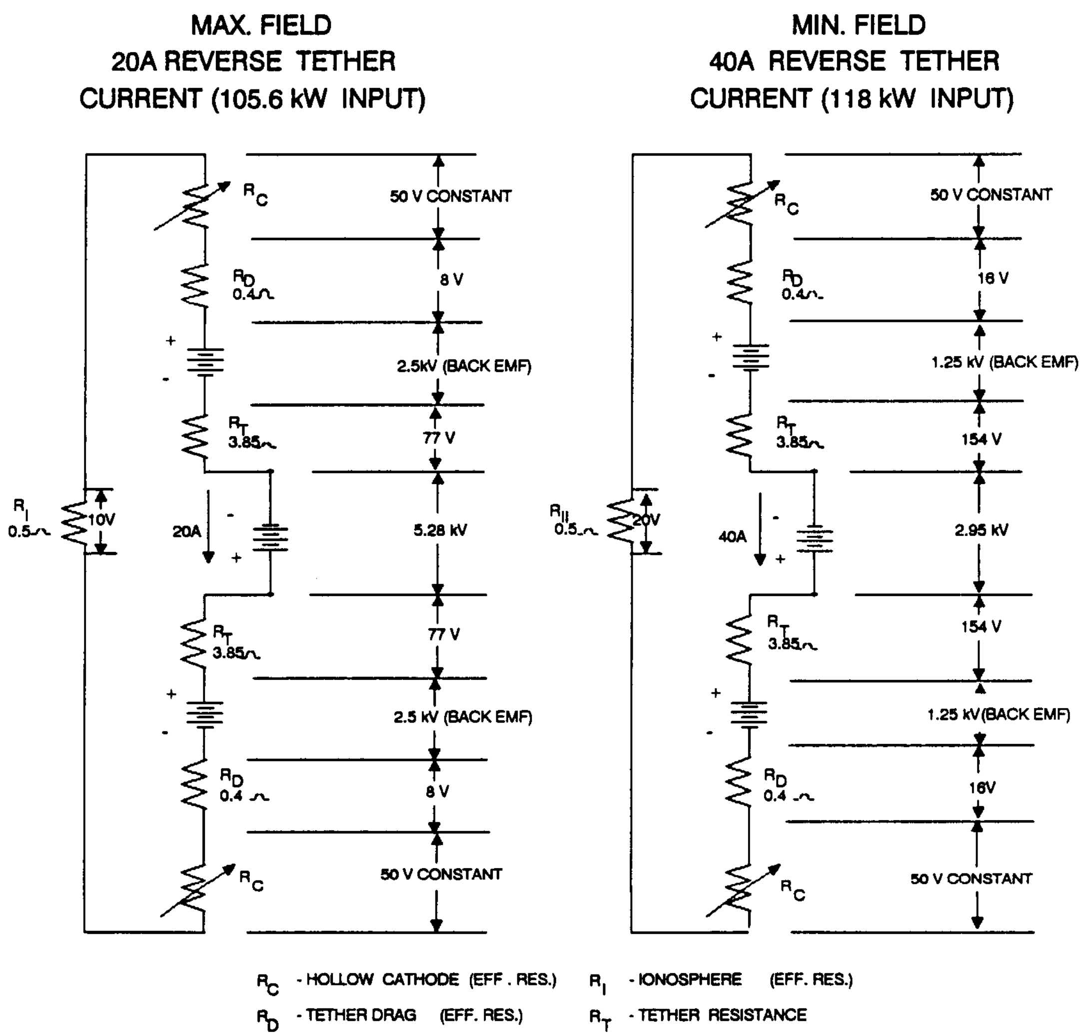


Figure 3.1-22 Tether In Motor Mode

have zero resistance for the equivalent circuit representations. Current flow is shown in the conventional + to - form (electron flow is the reverse of this).

It should be noted that the tether/converter interface efficiencies given are for this portion of the system only. The estimated converter efficiency of 96% must be factored in for the overall efficiency. For the generator mode in the maximum magnetic field the tether/converter interface efficiency is 94.5%. Overall efficiency including the converter is 90.9%. At the minimum magnetic field these numbers are 87.7% and 84.1% respectively. In the motor mode with maximum magnetic field, the tether/converter interface efficiency is 94.6%, with an overall 90.8%. For minimum field this drops to 84.7% and 81.3%, respectively.

Capabilities and limitations of the converter design depend almost entirely on the type of switching devices and rectifiers used. Developments in solid state components will determine the maximum capabilities of this design. It is possible that a bi-directional triac-type switching device will be available for use, eliminating the need for rectifiers, the switches being operated as synchronous rectifiers. Based on the data available at this time from the SS PMAD development activity, the tether converters are limited to the proposed voltage and current levels given in this report. The switching devices due to be tested this summer at Lewis Research Center are rated as follows:

- 1200 volts (the PMAD system will impose upwards of 630 volts on these devices, which is a reasonable derating for long life).
- 100 amperes peak current
- 25 amperes average continuous current
- 1 volt drop thru device at 20 amperes
- 1-1.5 microsecond turn-on and turn-off times, which is adequate for sine wave operation at 20 kHz.

These parameters were used in the converter loss estimates.

Converter module efficiency, in the generator and motor modes, has been estimated to be 96% +/- 2%. This figure agrees with efficiency estimates made for a 25 kW Lewis Research Center test unit. The efficiency will vary with the load, being highest at full load. We have estimated each converter module loss to be (at full load):

(Motor)	(Generator)	
360 W	400 W	@ 20 Amp tether I
480 W	520 W	@ 40 Amp tether I

This gives an average efficiency of 96% in either motor or generator mode, minimum to maximum field.

Breakdown of estimated losses in each converter module, based on use of the high speed SCR-type switching device presently in the final development stage,[11] are given in Table 3.1-1.

TRANSITION BETWEEN GENERATOR AND MOTOR MODES

Inasmuch as the PMAD system can accept or supply current from any available source as well as regulate the voltage into or out of these sources, transition between the generator and motor modes is simply a matter of regulating the voltage out-of or into the tether converter. This function will be handled by the Space Station Power Source Controllers (PSC), programmed to follow changes in the tether voltage, and regulate as required.

For example assume operation in the generator mode at maximum field, and maximum load on the tether converter. 5 kV at 20 A (625 V, 20 A per converter module) produces 440 VAC at 27.2 A from each of the eight tether converter modules coupled into the PMAD system. Now, if we increase the 440 VAC in the PMAD interface module to 464 VAC, and at the same time turn off the drive to all switching devices in the tether converters, we will then have a rectified 660 VDC across each VDC converter terminal. This produces 5.28 kV across the entire

	GENERATOR 20 A	GENERATOR 40 A	MOTOR 20 A	MOTOR 40 A
Q1 -	20 W	40 W	-	-
Q2 -	20 W	40 W	-	-
Q3 -	20 W	40 W	-	-
Q4 -	20 W	40 W	-	-
D1 -	-	-	20 W	40 W
D2 -	-	-	20 W	40 W
D3 -	-	-	20 W	40 W
D4 -	-	-	20 W	40 W
DR1 -	10 W	10 W	-	-
DR2 -	10 W	10 W	-	-
DR3 -	10 W	10 W	-	-
DR4 -	10 W	10 W	-	-
T1 -	150 W	150 W	150 W	150 W
L1 -	25 W	50 W	25 W	50 W
L2 -	25 W	50 W	25 W	50 W
C1 -	10 W	20 W	10 W	20 W
C2 -	10 W	20 W	10 W	20 W
R1 -	60 W	30 W	60 W	30 W
	======	=====	=====	=====
TOTALS	400 W	520 W	360 W	480 W
EFFICIENCY	96.8%	96%	97.2%	96.3%

Note: Converter efficiency has been rounded off at 96% in the report.
Note: C1 & C2 losses are ESR (equivalent series resistance)

Table 3.1-1 Converter Component Dissipations

converter stack (Figure 3.1-22), which now forces a reverse 20 A into the tether for motor operation. This can all be accomplished in a matter of milliseconds if desired. In fact, the AC from the station module could be adjusted for zero net current flow, or any value in between the two maximums. A command may need to be sent to the hollow cathode control electronics to re-configure when the direction of current changes. This could be accomplished by the PSC through the SS data bus to the FCA. The FCA would relay the command to the DCA.

FAULT PROTECTION

In the event of a gross fault condition in a converter module (usually a shorted semiconductor switch or rectifier) we propose incorporating a module by-pass switch, such as the SS Remote Bus Isolator (RBI) design, so that operation can continue at reduced power until such a time that the module can be replaced. This will increase the voltage across the remaining seven modules by only a factor of 1.14, which is well within the initial device ratings. Another option would be to automatically switch in the "spare" converter module when a fault is detected. This could be accomplished by keeping the "spare" by-passed until it is needed, and then switching it into the stack at the same time the defective unit is by-passed. Further study in this area will be needed to make a definite recommendation. The biggest unknown is the availability, size, and cost of RBI's large enough to handle the tether currents and voltages.

Converter Packaging

The tether converters are packaged as Line Replaceable Modules (LRM's), each measuring 24.1x39.4x41.9 cm (9.5 x 15.5 x 16.5 inches) excluding mounting feet (Figure 3.1-23). Five

LRM's are located at opposite ends of the Space Station on the Fixed Carrier Assemblies (FCA's). Four are active and one is a "spare".

The LRM's are mounted on a cold plate located near the tether attach point to minimize the length of high voltage lines. The cold plate will be similar to those being developed for the Space Station and will have the capacity to dissipate approximately 4 W/cm2 (25 W/in2) using two phase ammonia.[12]

Thermal management requirements are estimated at 540 watts per converter module. The total heat load for all four modules is 2160 W which is well below the IOC design number of 12.5 kW per payload attach point. All internally generated heat will be transferred to the LRM base where it will be absorbed by the cold plate and transferred to the SS main thermal utility bus. The estimated weights, power dissipation, and approximate sizes of the LRM components are shown in Table 3.1-2.

CONVERTER INSTALLATION

Prime design consideration has been given to the possibility of LRM replacement while in a space environment. The LRM has been provided with lifting eyes on the top surface. All electrical interconnections are made simultaneously on the rear surface of the LRM to a power distribution bus attached to the cold plate (See Figure 3.1-23).

DEVICE/ CIRCUIT	SIZE HxWxL (cm)	WEIGHT (kg)	POWER (W)
DQ1	1.3x3.8x6.4	1.5	40
DQ2	1.3x3.8x6.4	1.5	40
DQ3	1.3x3.8x6.4	1.5	40
DQ4	1.3x3.8x6.4	1.5	40
C1	7.6x16x17.8	2.3	10
C2	7.6x16x17.8	2.3	10
L1	10.2x12.7x12.7	9.1	50
L2	10.2x12.7x12.7	9.1	50
T1	10.2x16.5x17.8	10.0	150
Bias/Control	4.6x15.2x15.2	0.7	10
R1	2.5x2.5x7.6	0.5	60
Circuit Breaker	2.0x10.2x15.2	0.6	
Driver 1	2.0x5.1x7.6	0.1	10
Driver 2	2.0x5.1x7.6	0.1	10
Driver 3	2.0x5.1x7.6	0.1	10
Driver 4	2.0x5.1x7.6	0.1	10
Converter Box	24.1x39.4x41.9	19.1	
Wiring Harness	N/A	4.5	
TOTALS		64.6 kg	540 W

Table 3.1-2 Component Dimensions & Power Dissipation Est.

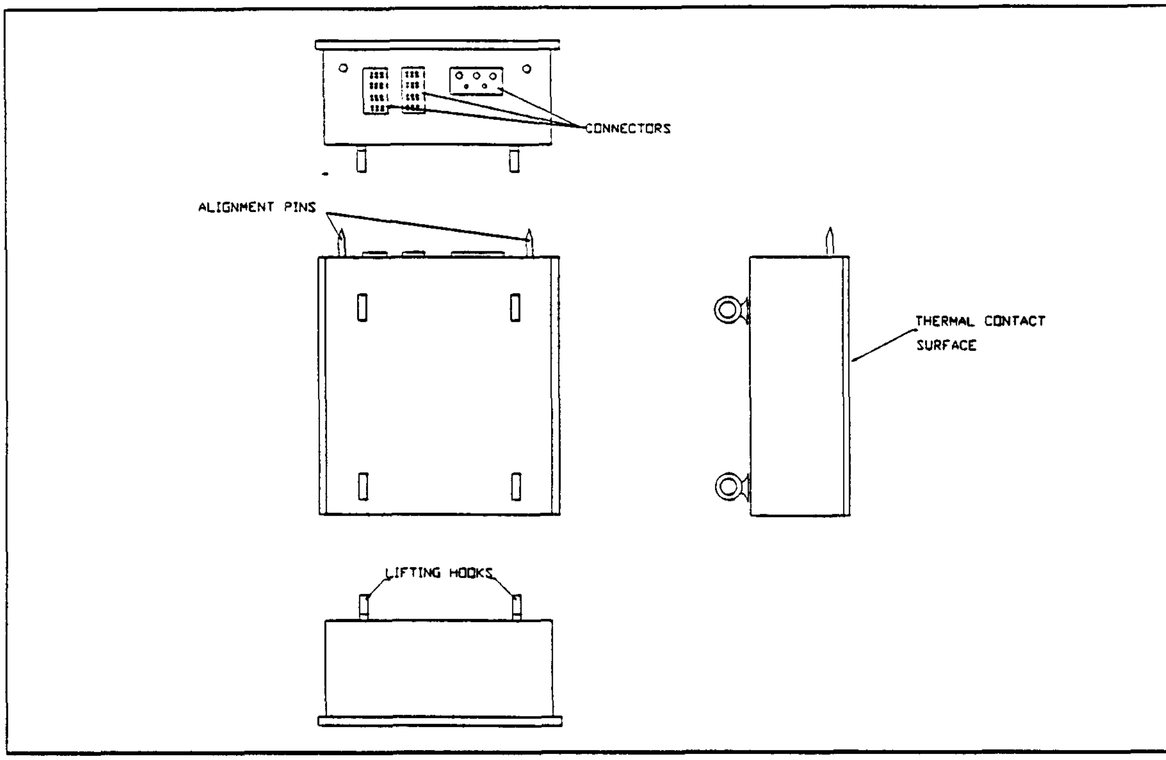


Figure 3.1-23 Converter (LRM) Configuration

Removal of an LRM in space could be accomplished with an electro-mechanical actuator located in the cold plate. The actuator would consist of an electric motor, gear reducer, clutch mechanism, CAM locks and a lead screw. The electric motor, when initiated, would rotate the lead screw unlocking the CAM locks (located on each side of the LRM in a guide assembly), and then back out the LRM from the power distribution bus. The LRM would use guide pins located on the LRM to position the connectors for remote installation of the units. All electrical and fiber optic connectors would be mechanically floating to eliminate binding during installation. A manual engagement/disengagement system, using a suitable socket-type wrench, would be included in case of electric motor failure or binding.

LRM HOUSING DESIGN

The LRM housing enclosure consists of two parts; the cover and the box. The cover is aluminum plate (6061 alloy), machined flat with EMI baffles on the faying contact surfaces.

The housing components (sides, ends, bottom and internal partitions) are machined and then the components are assembled using an aluminum vacuum brazing procedure, external features are machined and then surface treated. The vacuum brazing procedure will produce a very rigid housing. This construction will provide a continuous thermal path through the sides and bottom and EMI tight joints. Housing venting will be accomplished using EMI tight vent plugs located on each of the LRM end plates.

Partitioning within the LRM housing is limited to that area surrounding the capacitors (Figure 3.1-24).

CAPACITOR DESIGN

Capacitor configuration incorporates a design developed by Lewis Research Center for high frequency, high power capacitors.[13] The design

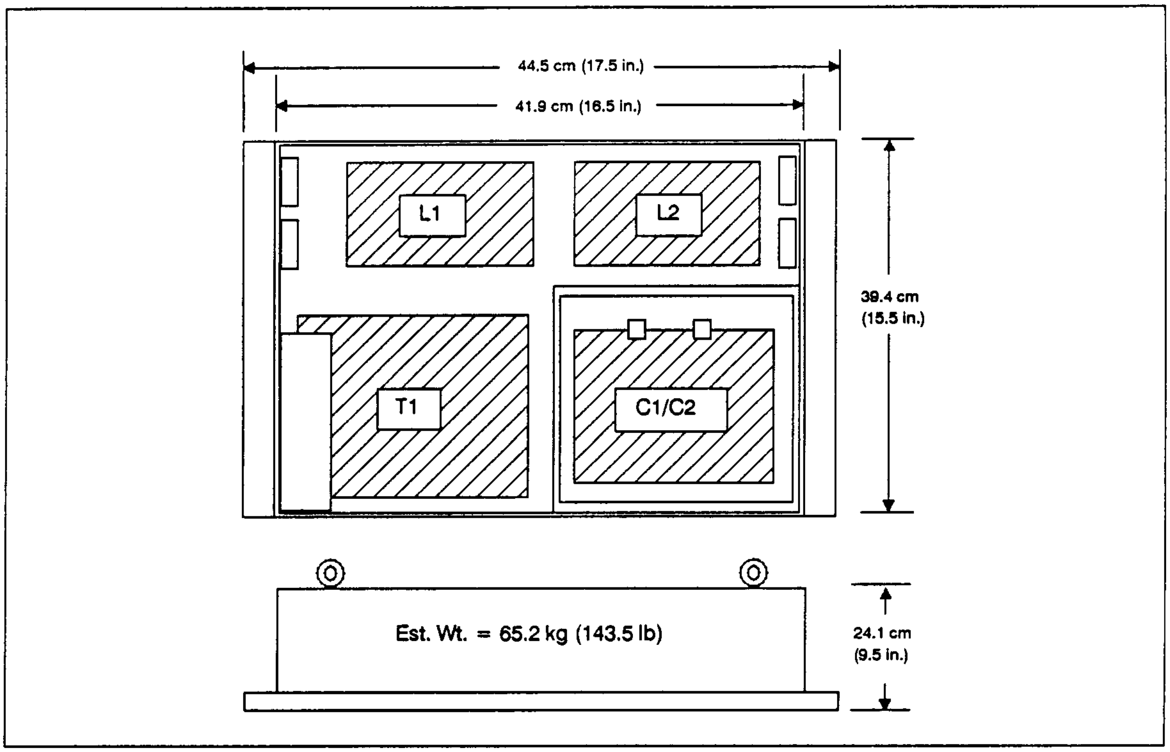


Figure 3.1-24 LRM Packaging Design

concept uses a split foil and a floating foil with multiple cells enclosed in a stainless steel container (Mat'l 304L) filled with monoisopropyl biphenyl (MIPB) dielectric impregnate. The capacitors are fastened to the LRM housing with ten 10-32 UNC screws. Electrical connections are two insulated 3/8 - 24 UNF studs located on the case.

INDUCTOR/TRANSFORMER DESIGN

The LRM magnetics will incorporate design information made available through NASA.[14] This design approach incorporates methanol filled, stainless steel heat pipes integrated into the winding to draw core heat directly to the cooling surface. An electrostatic shield, made of a thin sheet of copper is attached directly to the heat pipe. Two heat pipes are placed between the primary and secondary windings over insulation and formed about the winding. The two shields collect the heat generated in the coil winding wire and transfer it to the base plate.

3.2 System Hardware Description

The following sections will describe the mechanical configuration for the Electrodynamic Tether System (ETS).

Configuration Selection

The electrodynamic tether system was designed to the following requirements:

Low cost was a prime consideration (implies simplicity)

- Maximize use of flight qualified hardware
- Minimize Space Station modifications required to implement the tether system
- Design for hardware commonality
- Design system with considerations for on-orbit serviceability
- Design hardware to accommodate a tether of .927 cm (.365) in. od insulated aluminum 20 km long (10 km up and 10 km down)

- Design system for an OMV assisted deployment to simplify deployment and operations
- Optimize configuration for weight and cargo bay length to minimize launch costs
- Configure system to minimize EVA requirements both for transfer onto the Space Station and tether deployment
- Maximize tether tip mass to increase stability during operation
- Assume a plasma generator gas supply of 1 to 5 yrs.

Four separate configurations were considered, shown in Figure 3.2-1, before a baseline was selected. All four concepts were capable of accomplishing the tether mission, however the selected baseline approach was superior to the other in most areas.

Concept #1 is potentially the lightest approach of the four concepts and interfaces easily with the Space Station through a Station Interface Adaptor (SIA). The SIA is a BASD concept for payload attachment to the Space Station developed under the Work Package 3, Phase A, studies. The configuration baselines a reel for tether storage similar to TSS-type tether systems. The inertia of the reel during initial start-up and the constantly varying inertia during deployment would probably require additional control hardware, even while using the OMV to pull out the tether. It is also not known if the OMV can latch onto a small package such as the Plasma Contactor Module.

Concept #2 is the heaviest of the concepts and requires a hardware modification to the Space Station truss for mounting the CRRES cradle. It does have the advantage of being the only concept whose structure is already designed, qualified, and capable of handling the payload mass without modifications.

Concept #3, based on the spacelab pallet, would require additional structure to be added to span the pallet for accepting the loads of the tether system during launch. This system also interfaces with the Space Station on the SIA structure as in concept #1 and uses the OMV to deploy a canister containing the tether and the plasma generator module. Unlike concept #1, the tether is held on a fixed spool instead of a reel. The tether is payed off the flange of the spool, thereby eliminating inertia concerns and the additional mechanisms of the reel approach. Also, this system allows both ends of the tether to be permanently secured so that high voltage slip rings and post deployment connections are eliminated. Due to the cargo bay length required by the spacelab pallet, this concept has the highest launch costs of the four approaches.

Concept 1A (the baseline approach) incorporates the strong points of the others plus some additional features. The approach is to use the SIA Space Station hardware as in #1 and #3, the deployed tether spool as in #2, #3, and to minimize cargo bay length (and so launch costs) as in #1. The concept is also optimized for maximum serviceability. All components are EVA/RMS accessible in the event of a failure. The Plasma Contactor Module, as well as being refillable, can also be upgraded from a 1 year supply to a 5 year supply with essentially no structural modifications. The hardware is flown in the Shuttle as an integrated unit. Once the assembly is mounted to the Space Station SIA and docked with the OMV, explosive bolts release the Deployed Carrier Assembly (DCA) from the Fixed Carrier Assembly (FCA). The OMV, docked with the Deployed Carrier Assembly, is now able to deploy the tether by moving away from the Space Station. Although only one keel fitting on the assembly is used during launch, both the fixed and the deployed carriers have a keel fitting. They also each have a grapple fixture and latching hardware so that after deployment it is still possible to service or retrieve either carrier assembly in the Shuttle or onto the Space Station.

To summarize, the baseline approach was selected based on the criteria below:

- Structure is based on standard Space Station payload adaptor hardware (deck carriers)
- Interfaces to standard Space Station payload port (SIA)

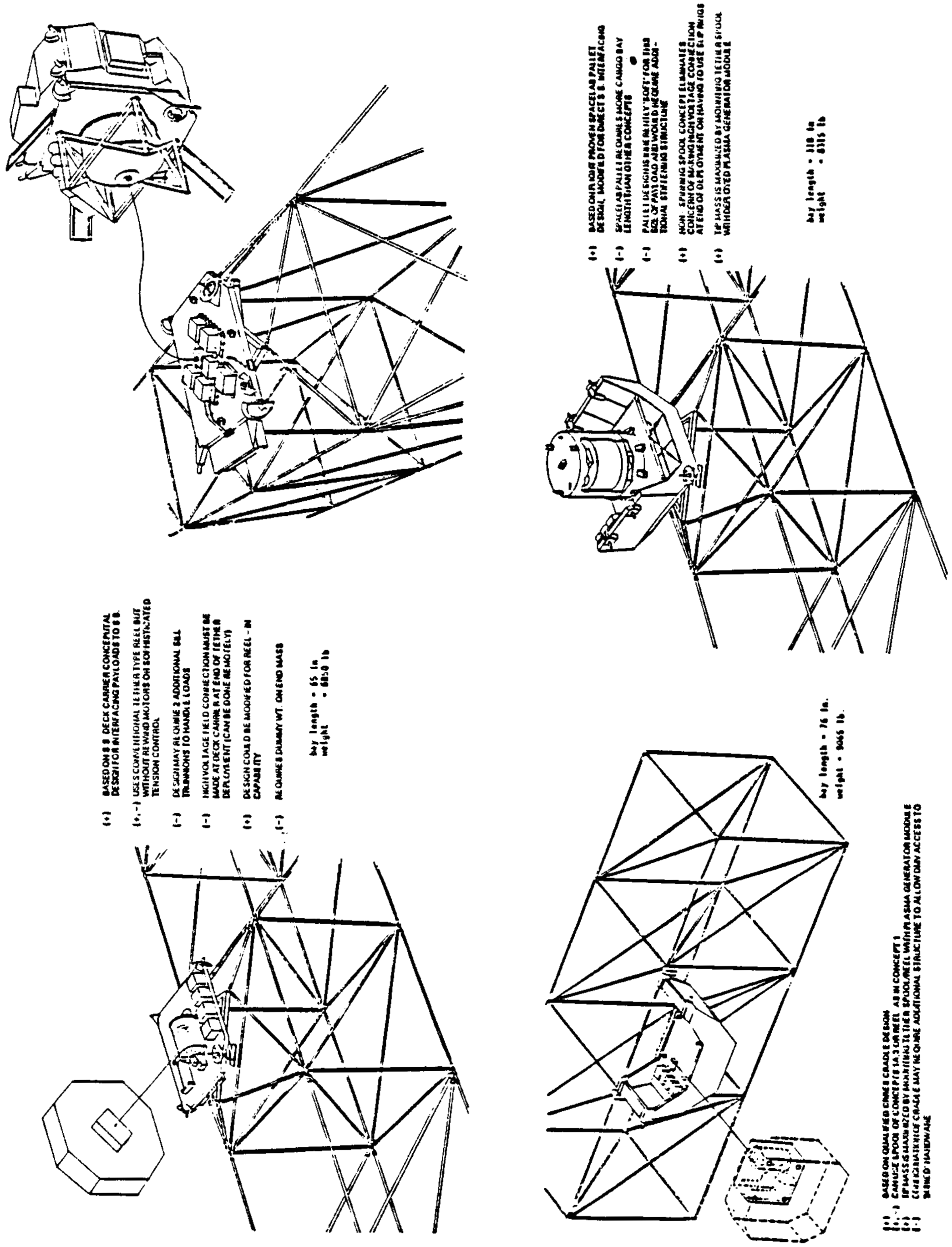


Figure 3.2-1 ETS Mechanization Concepts

- Maximizes tip mass weight to avoid dummy mass requirement
- Easily accommodates upgrade to 5 yr. plasma gas supply with space available for even greater life
- Servicing capability enhanced by modular configuration (either carrier can interface with SS or Shuttle)
- Spool concept avoids the need for high voltage slip rings or field connections

Integrated Carrier Assembly (ICA)

The baselined concept, shown in Figure 3.2-2, is carried in the shuttle cargo bay as a single unit referred to as the Integrated Carrier Assembly (ICA). Figure 3.2-3 illustrates how the ICA fits into the shuttle bay. Two ICA's, one deployed 'up' one deployed 'down' and an interconnect cable make up the Electrodynamic Tether System. Figure 3.2-4 illustrates this terminology. The ICA is made up of 3 major hardware assemblies, plus the tether. The assemblies are the Fixed Carrier Assembly (FCA), the Deployed Carrier Assembly (DCA), and the spool assembly.

Fixed Carrier Assembly (FCA)

The fixed carrier assembly (FCA) is adapted from a design of the Space Station Deck Carrier intended to interface medium and small sized payloads to the Space Station truss. The deck carrier is a simple, planar, honeycomb structure with edge closures and face sheets. The aluminum honeycomb structure offers a high stiffness to weight ratio.

The deck carrier interfaces onto the Station Interface Adaptor (SIA) as shown in Figure 3.2-5. The SIA is a passive structure with connectors to make the fluid and electrical interface between the payload on the deck carrier and the Space Station. The SIA uses a single central trunnion and 3 'Y' guides for the deck carrier structural interface. The deck carrier latches to the SIA trunnion with a berthing latch identical to the ones used on the Flight Support System (FSS) for servicing the MMS spacecraft. The 3 alignment pins (see Figure 3.2-6) used to interface with the SIA Y guides are arranged similar to the MMS S/C, i.e., on a 91.4 cm (36.0 in) radius and 120 degrees apart.

Figure 3.2-6 also shows the redundant electrical connectors and the motor driven fluid connectors for the deck carrier thermal interface. The electrical connectors provide the interfacing for Space Station power and data lines and for the high voltage line that interconnects the upper and lower tether systems. This line may be routed with the other S.S. cabling during the on-orbit assembly phase, or installed separately. The Space Services Module (SSM) contains the control boxes to provide the necessary processing, housekeeping, and data management between the Space Station and payload. This module is assumed to be SS supplied equipment.

The payload side of the deck carrier is open to accept any arrangement of boxes or instruments that can fit within the orbiter envelope. The Electrical Flight Grapple Fixture (EFGF) and the Shuttle Umbilical Release System (SURS) connector, for electrical interface to the orbiter, do require an access envelope however. The four required LRM boxes, the control electronics box, and the circuit breaker/tether attach box all mount onto the centrally positioned cold plate. A fifth redundant LRM is located adjacent to the cold plate. Each LRM is mounted in a latching mechanism that provides an electrical and structural interface to the box while allowing the box to be easily removed while on orbit for servicing.

The latching mechanisms will borrow technology from on-going servicing studies. Four pedestals surrounding the cold plate provide the interface points for the other half of the tether system containing the tether, spool, and plasma generator. Each pedestal houses a set of NSI activated release nuts to separate the structure halves after the system is set up on the Space Station. A tether guillotine is provided to release the tether from the FCA in an emergency. Figure 3.2-7 and 3.2-8 show the FCA mounted onto the Space Station in pre-deployment configuration.

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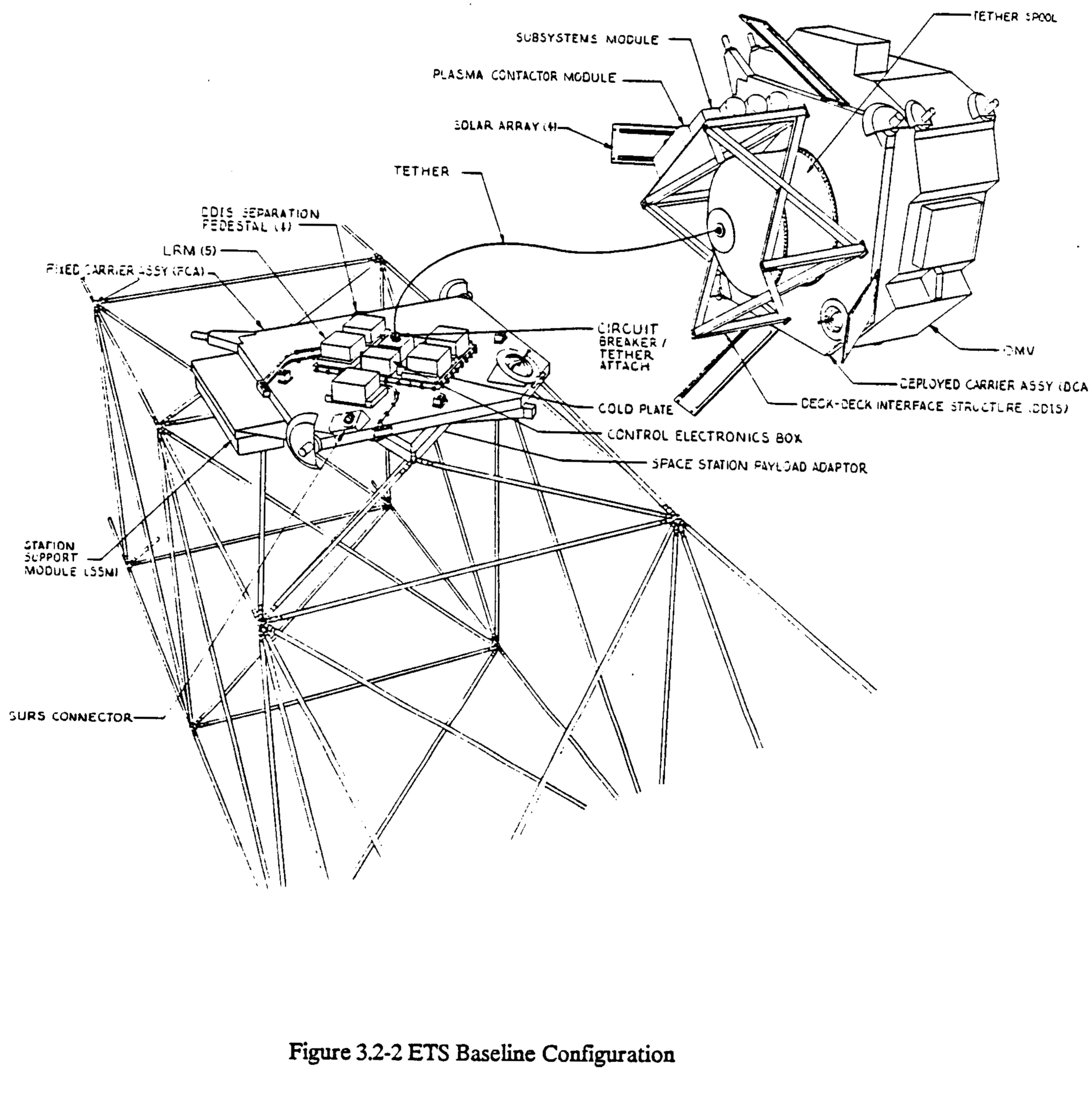

Figure 3.2-2 ETS Baseline Configuration

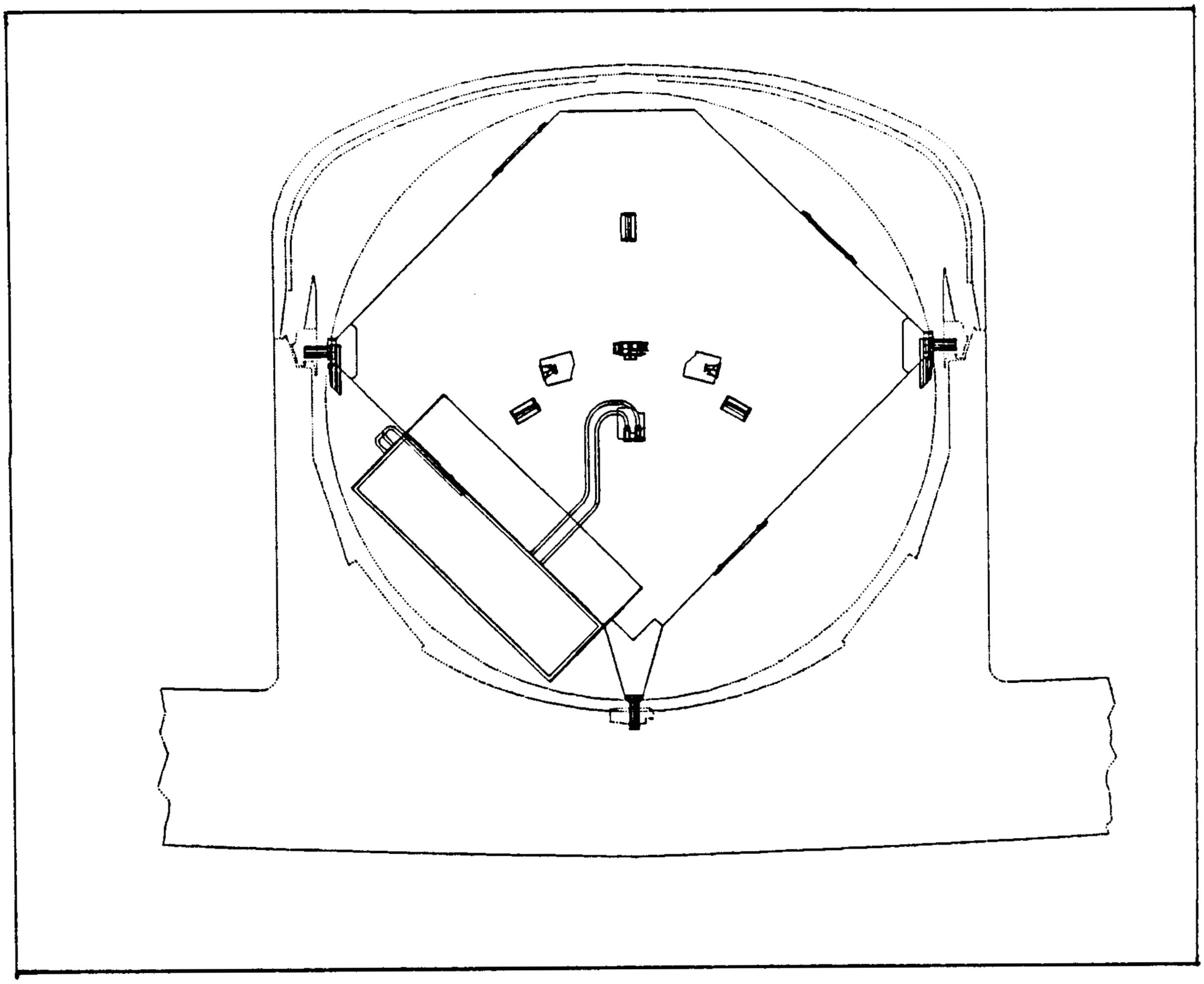

Figure 3.2-3 Shuttle Cargo Bay View

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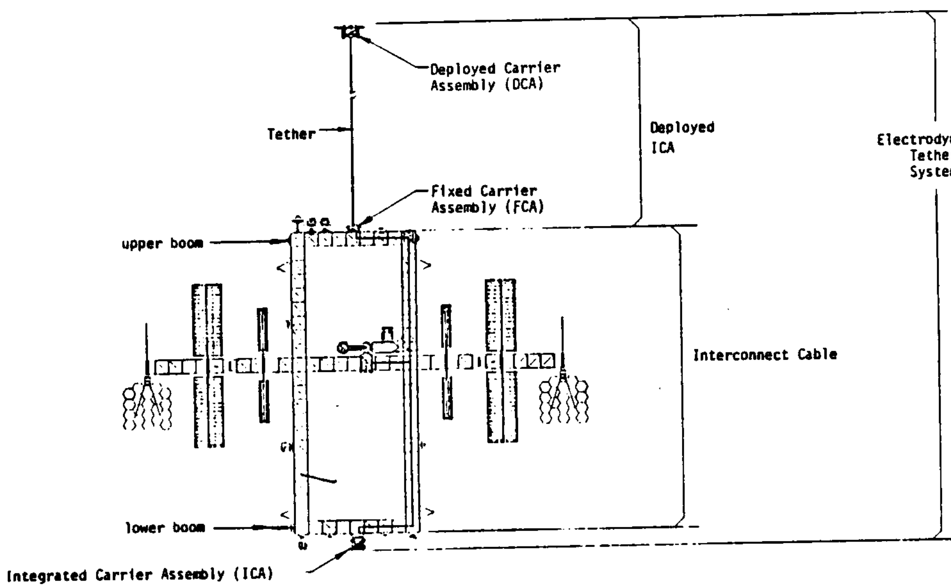

Figure 3.2-4 ETS Terminology

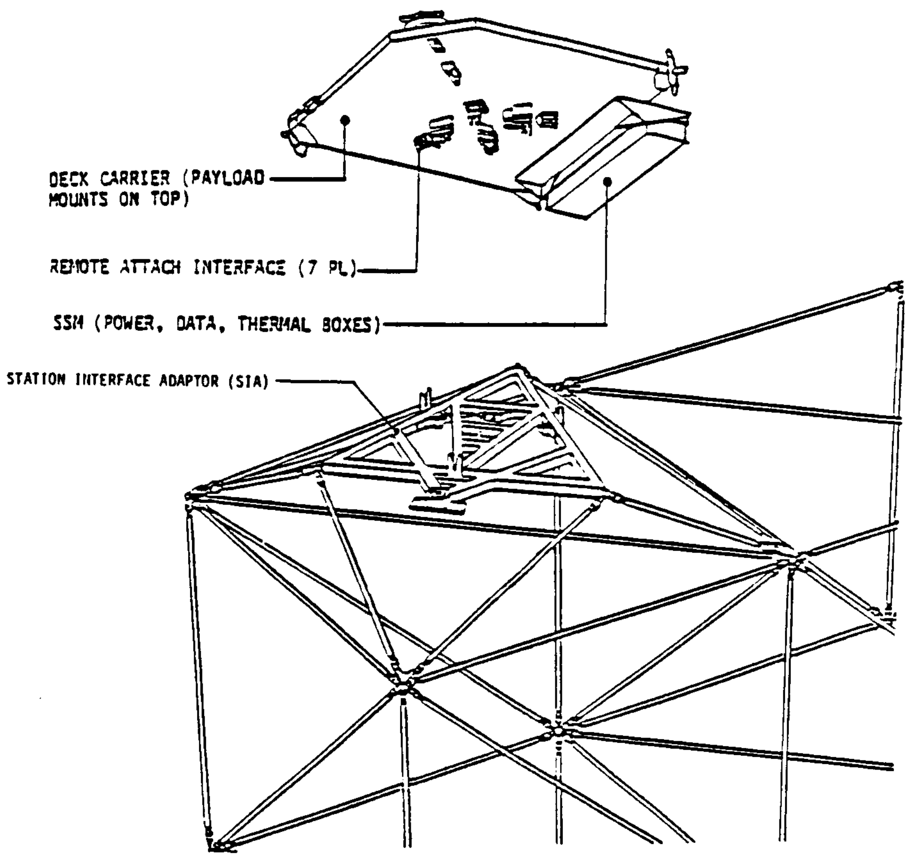

Figure 3.2-5 Deck Carrier - SIA Interface Components

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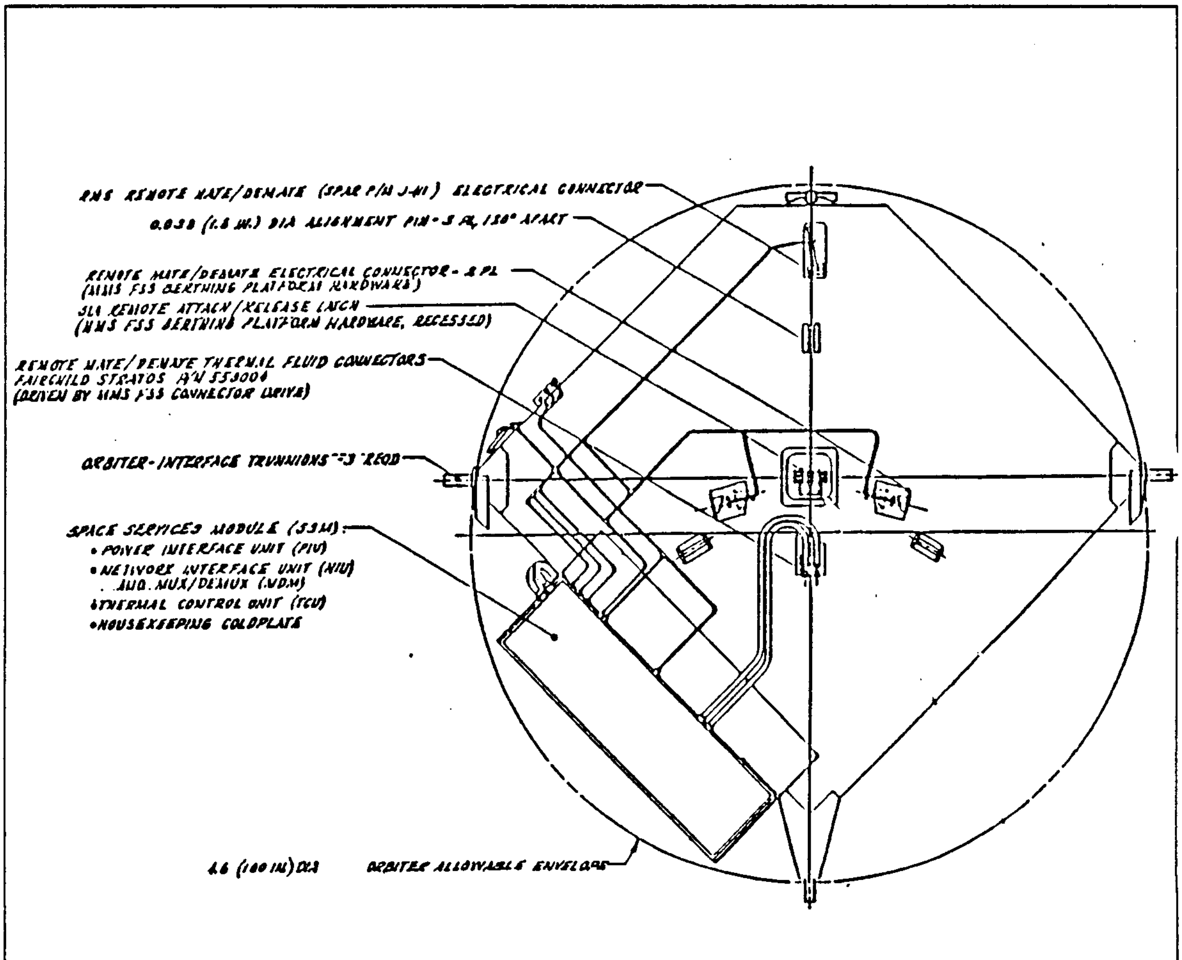

Figure 3.2-6 SIA Interface Side of Deck Carrier

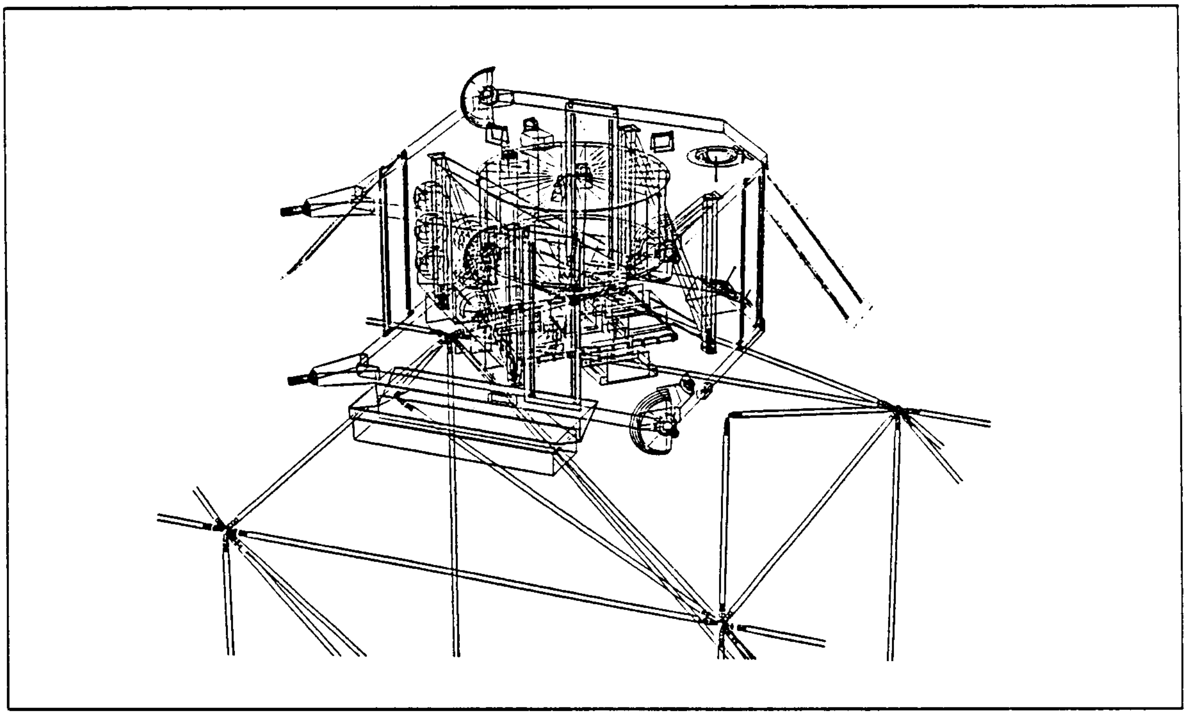

Figure 3.2-7 On-Orbit, Pre-Deployment of ICA

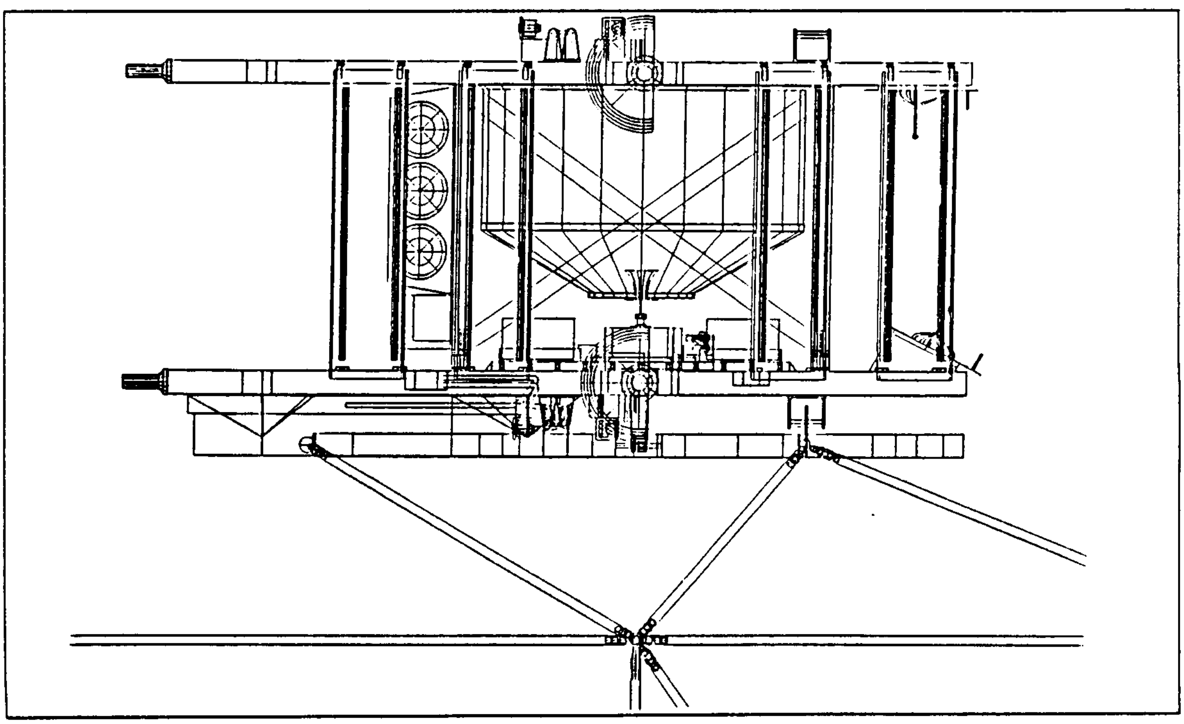

Figure 3.2-8 On-Orbit, Pre-Deployment, Side View

Deployed Carrier Assembly (DCA)

The deployed carrier assembly (DCA) consists of 6 major subassemblies; the deck carrier, spool, deck-to-deck interface structure (DDIS), plasma contactor module, power system, and subsystems module.

DECK CARRIER

The DCA deck is structurally identical to the FCA deck and has the same mechanisms on its 'back' side; three alignment pins, one FSS berthing latch, two electrical connectors, and a fluid connector. These are provided for OMV interfacing during the tether deployment or for servicing. The fluid connector provides for a plasma generator gas recharge capability using the OMV. The mechanisms could allow the DCA to be docked to the Space Station on another SIA in the event of a tether break or major system failure early in the deployment procedure.

The DCA also has a keel fitting and grapple fixture that are unnecessary for normal operations, but allow for recapture into the STS cargo bay, MRMS assist during deployment and orbital maintenance. It would be possible to deorbit the DCA, in the STS cargo bay, with only 2 longeron trunnions if the tether spool were empty.

SPOOL ASSEMBLY

The spool is intended as a housing/transporter for a 10 km (5.4 nmi) long by .965 cm (.38 in.) diameter tether. The configuration allows for the tether to be payed off the flanged end of the spool as shown in Figure 3.2-9. This potentially eliminates the need for a rotating reel or any moving parts or mechanisms. Further study may show a need for a tension creating device or brake near the exit nozzle of the spool. The exit nozzle is fabricated from a type F tool steel for high wear/low friction characteristics. The spool assembly is fabricated primarily from structural aluminum. The 76.2 cm (30 in.) diameter hub carries the loads during launch from the 1451 kg (3200 lb.) tether.

Six tether launch retainers, spaced evenly around the perimeter of the wound tether, secure the tether from shifting during launch. The retainers are air bags that are deflated with pyrotechnics just prior to deployment. The spool concept allows both ends of the tether to be secured on the ground, thereby eliminating the need for high voltage slip joints or field connections. The Spool Assembly is mounted onto the DCA in two locations. The 12 hub attachment bolts provide the primary structural attachment. The 24 external peripheral bolts assist with the launch loads taken through the launch retainers into the outer case.

An alternative spool concept was briefly considered but would require further study to ascertain its advantages over the baselined concept. Looking similar to the concept shown in Figure 3.2-9, the alternative design would use an expanding mandrel in place of the 76.2 cm (30 in.) hub. Once on orbit, the mandrel would be drawn inwards to expose the inner wraps of the tether. The tether would feed off the inner wraps first and through a similar type of exit nozzle. This type of system trades off a simpler feed route for the tether against a slightly more complex tether restraint mechanism. This type of system may also be more prone to tangling during pay-out since adjacent wraps will be unconstrained.

DECK-TO-DECK INTERFACE STRUCTURE

The primary function of the DDIS is to couple the Fixed Carrier Assembly with the Deployed Carrier Assembly as one integrated unit. This simplifies handling prior to tether deployment, but more importantly, launch costs are reduced by minimizing bay length and weight. As separate assemblies, each Deck Carrier would require 4 longeron trunnions, adding bay length and weight over the proposed system. The DDIS structure consists of 10.2 x 10.2 x 0.635 cm (4 x 4 x .25 in) wall aluminum tubing plus the hardware for the separation system.

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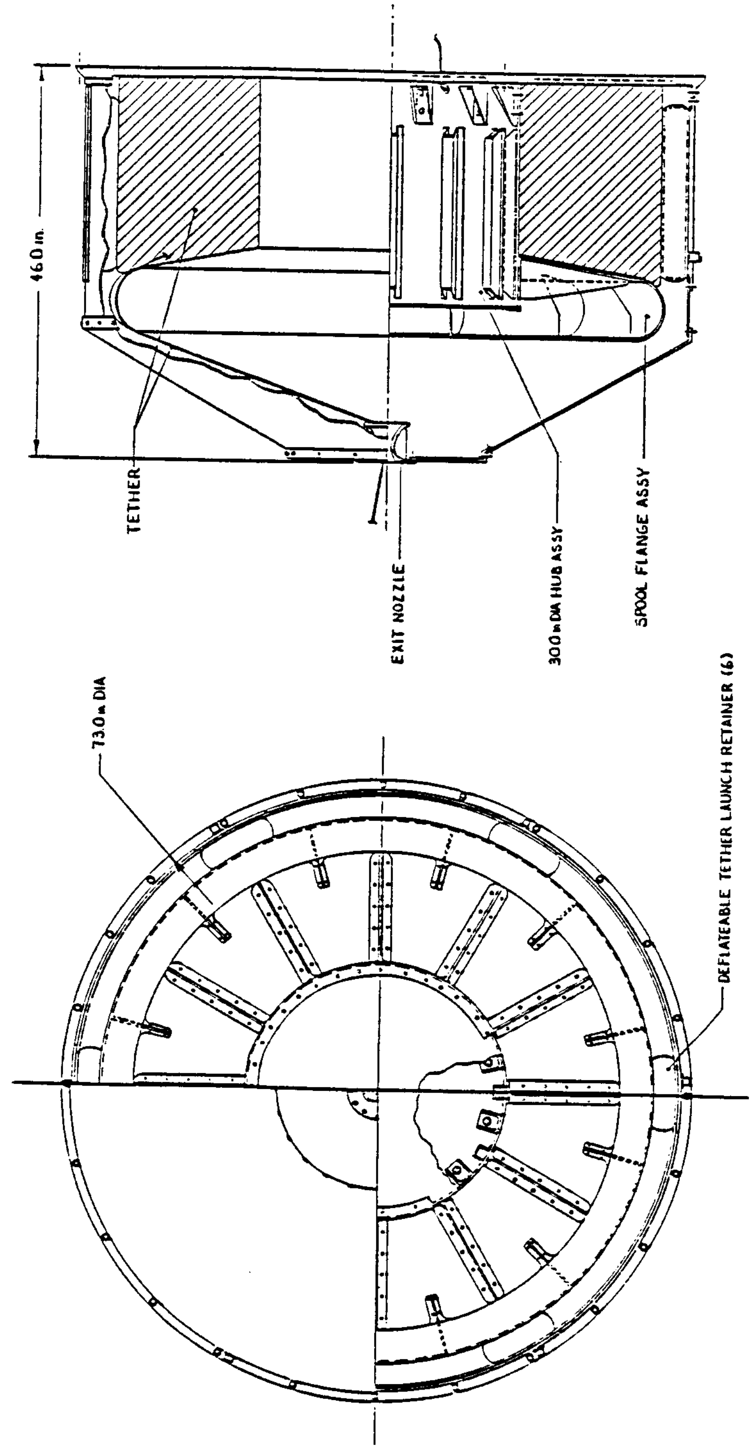


Figure 3.2-9 Spool Structural Assembly

PLASMA CONTACTOR MODULE

The Plasma Contactor Module is configured as an integrated unit for ease of ground test and integration onto the DCA. The configuration creates an on-orbit replacement option, although this capability is not baselined. The module is a structural frame consisting of the plasma contactor, argon supply tanks with regulators and valves and control electronics. Lines from the supply tanks are routed to the back side of the DCA to allow for possible remote recharging from the OMV.

The two tanks are 43.2 cm (17 in.) OD spherical titanium capable of holding .036 cu. meters (1.27 cu. ft.) each of Argon at 20.7 MPa (3000 psi) and standard temperature. These tanks should provide a 1 year capability. A five year capacity module has also been configured, using three 30.5 cm (12 in.) diameter cylindrical tanks each 1.524 m (5 ft) long. This 5 year module attaches to one side of the DDIS. As all four sides of the DDIS structure are open and accessible, it would be fairly simple to extend well past a 5 year capability.

Figure 3.2-10 is a schematic of the Plasma Contactor Module and its interface with the Command and Data Handling (C&DH) equipment. The system is completely redundant to provide a high probability of meeting a 5 to 10 year life goal.

DCA POWER SYSTEM

The DCA will require power for subsystems and for operation of the plasma contactors. The estimated powers are shown in Table 3.2-1.

During actual operation of the ETS the power required for operations can be tapped directly from the tether. However, when the tether is inoperative or changing current flow direction this power will have to be supplied from an external source.

There are several possibilities for the source of this external power. The power could be delivered from the SS through the FCA power

Item	Peak Pwr. (Watts)	Duty Cycle (%)	Ave. Pwr. (Watts)
C&DH	35.0	100	35.0
Communications	5.0	10	0.5
Plasma Contactor (start-up only)	100.0	10	10.0
TC Heaters	100.0	5	5.0
		Total	50.5
Regulator Losses (70% Efficiency)		19.5	
		Total	70.0

Table 3.2-1 DCA Power Requirements Estimate

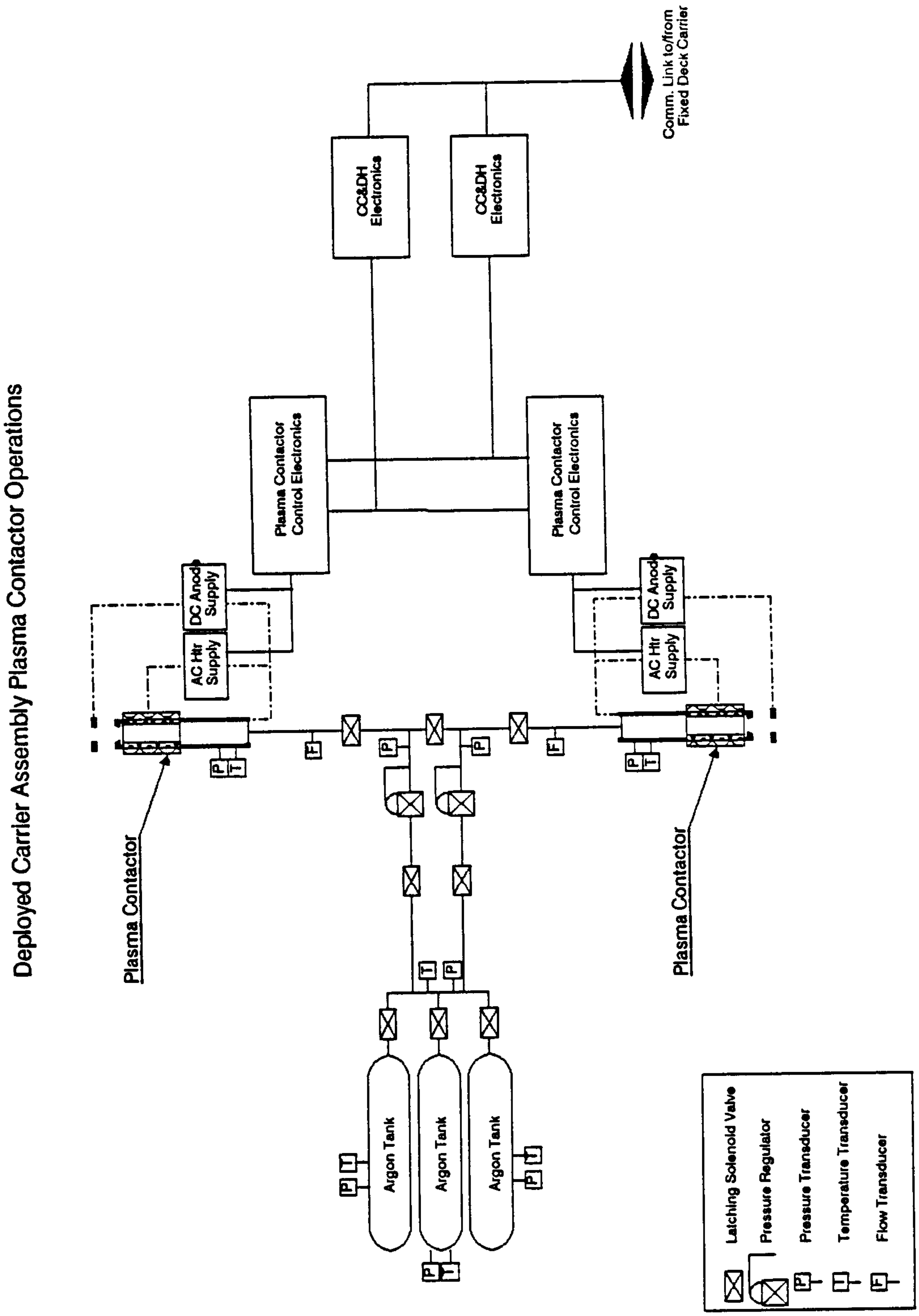


Figure 3.2-10 Plasma Contactor Module (DCA)

interface using a separate set of conductors, it could be supplied by batteries, or it could be supplied by solar arrays mounted on the DCA.

SPACE STATION POWER

The power requirements are quite low so thin wires could be used to conduct the current from the SS to the DCA. However, there are several drawbacks associated with this approach including, logistics of multiple tether deployment and repair, high induced voltages in the line, complete loss of power to DCA if the tether is severed, and conductor impedance characteristics.

Simultaneous deployment of multiple conducting tethers presents many complications in the areas of system configuration, attitude control, uneven tensions in the tethers, repair and servicing, and increased aerodynamic drag.

Also, any power lines running from the SS to the DCA will be subject to the same induced voltages as the main tether. The total voltage will amount to several kV over the 10 km distance. The SS power system would have to be isolated from this voltage. This could be accomplished by using the Space Station 440 VAC 20 kHz bus voltage for transmission and capacitors in series with the lines to isolate the tether DC voltage level. A final concern with supplying the DCA system power from the SS is that the DCA will be completely dead if the power lines are severed. This would probably lead to damage of the DCA subsystem equipment due to temperature extremes experienced before the lines could be repaired.

BATTERY POWER

Batteries could be used to supply power to the subsystems during non-operation of the electrodynamic tether, and then recharged when there was current flowing in the tether. The limited operating time available with this approach would restrict the operation and repair scenarios for any reasonable number of batteries.

SOLAR ARRAY POWER

A solar array power system is recommended to supply subsystem power during periods of tether inactivity or when the tether current is being switched between generator and motor modes. A solar array system will be sized to handle the power requirements during periods when electrodynamic tether current is not available. If it eventually proves impractical or undesirable to tap power from the tether then the system can easily be resized to handle the total DCA power requirements.

Gravity gradient forces should hold the DCA in an earth-oriented position at all times. However, the yaw attitude cannot be determined in advance without an attitude control system. Therefore, the array positions and sizes are selected to take this unknown factor into account. The environmental and design factors used for array sizing are presented in Table 3.2-2.

Orbit Altitude	500	km
Inclination	28.5	degrees
Solar Constant	1355	W/sq meter
Solar Cell Eff.	10	%
Cell Packing Factor	.9	
Battery Charge Eff.	85	%
Max. Beta Angle	52	degrees

Table 3.2-2 Power System Design Assumptions

The optimum location of the solar array panels is DCA dependent since one is deployed upward and one downward. The location chosen for the arrays should avoid interface problems with the OMV and SS equipment during launch and retrieval of the DCA. In addition the projected area in the velocity direction should be minimized to reduce aerodynamic drag.

Based on the above considerations and the unpredictability of the DCA yaw orientation a location on the "sides" of the DCA was chosen for the array panels. The panels are in a stowed condition for STS launch and positioning of the ICA on the Space Station. The panels are deployed into their operational orientation during the separation maneuver at the start of ETS deployment. The panels are located on all four sides of the DCA to make the system omnidirectional. The deployment angle of the arrays (40 degrees from nadir) was chosen to minimize the total array area. Note that the arrays for the upward DCA are hinged on the deck side and the downward DCA arrays are hinged away from the deck (i.e. the arrays must be deployed to look skyward).

Figure 3.2-11 presents a plot of the average output of this array configuration for various beta angles. Based on this plot and the orbital information of Table 3.2-2 the area required to meet the requirements of Table 3.2-1 with a 10% margin (90 watts output) is .8 square meters per panel.

The baseline design has four aluminum honeycomb panels 68.6 x 144.8 x .635 cm (27 x 57 x .25 in). The panels are latched to the FCA for launch and are released for deployment when the DCA separates from the FCA.

The remainder of the power system consists of redundant 6 amp-hr batteries, a shunt radiator, and a simple charge controller circuit.

SUBSYSTEMS MODULE

The subsystems module contains the electronics for the Command and Data Handling and Communications. It is anticipated that this equipment will be simple and quite small.

The C&DH will take care of sending/relaying commands to the plasma contactor control electronics, controlling the various valves and regulators, and monitoring the health of the DCA equipment. Housekeeping information

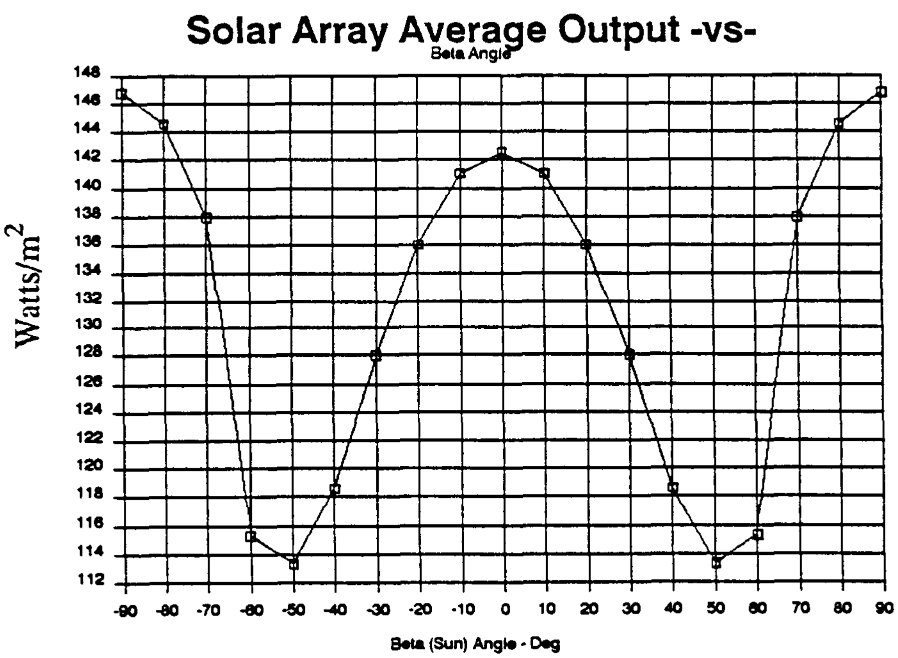


Figure 3.2-11 Solar Array Output vs Beta Angle (40 cant)

will be stored in the C&DH memory for transmission to the FCA at regular intervals.

The communications equipment is baselined as a small RF transmitter and receiver. The same type of equipment will be located on the FCA. The DCA receiver will be operated constantly, but the transmitter will only operate when a request is sent from the FCA, or for anomaly reporting. This will reduce the RF noise in the vicinity of the SS. Other options are possible for the communications link including; optical links, direct electrical links through a separate communications line, or possibly the tether itself. These options were not considered in detail in this study.

Tether

The tether is baselined to be 10 km x .965 cm (.38 in.) OD diameter including insulation. The tether is composed of two primary parts; conductor and insulation. Some tether design considerations include the following;

- 5 to 10 yr. life (on-orbit maintenance)
- 5000 Volt Rating
- 15 in. bend radius without permanent set
- designed for minimal weight

A major design driver for the tether is repair and maintenance considerations. It has been assumed that some type of robotic system will be used for these operations. Some concepts are discussed in the operations section of this report.

CONDUCTOR

The conductor will be fabricated from small diameter aluminum wires, using the bunch technique.[15] The size of the conductor is dictated by the power and efficiency requirements.

INSULATION

Below is a listing of some design considerations for electrodynamic tether insulation.

Weight

- Low weight/minimum drag area desired

Bend Radius

- 15 inches minimum

- No permanent set

Fabrication

- Ease of constructing 10 km cable

- Possibility of sculptured tether insulation

Repair/Refurbishment

- Should be repairable by robotic means

- Will extend useful lifetime

Electrical Characteristics

- maximum operating voltage

- maximum current

Thermal Properties

- Low alpha/epsilon ratio desired for maximum efficiency

- Long duration mission (10 years)

Coefficient of Thermal Expansion

- Differential expansion with conductor

- Repeated earth shadow cycles

Long Term (5 to 10 years) Stability

- Synergistic effects

Testing/development implications

Storage Problems

- Cold flow or shape change

Atomic Oxygen (AO) Susceptibility

- Space Station Altitude and Inclination

- Long duration mission

- Coatings could be damaged by debris/deployment

Ionizing Particle Resistance

- 10 year exposure of up to 2.2E + 7 rads

- Must retain

Flexibility

Electrical properties

Thermal properties

UV Stability

- Long-term stability of thermal finish

- UV effects on mechanical/electrical properties

Orbital Debris Damage Threshold

- Pin-hole effects

- Effect on AO resistance

Outgassing/Contamination Potential

- Outgassing from insulation and cable interior

- Compatible with other SS contaminants

Ammonia molecules

Water molecules

Others

Depressurization During Launch

- Proper venting during launch

The SS advanced development program is evaluating a variety of materials for long term space applications. This information will be quite valuable in making a preliminary choice of the tether insulation design. If possible it should be kept a single material, possibly coated, since any orbit repair will be hindered if a multi-layered design is used.

Baselined Concept Mass Properties

The mass properties for the baseline design are presented in Table 3.2-3.

Interconnect Cable

The interconnect cable provides the electrical interface between the lower FCA and upper FCA. The cable must conform to all Space Station requirements for electrical cabling. The cable will be designed for 5000 V at 60 amperes. Due to the electrical hazard potential of this cable, special insulation for impact protection will be required. The location and method of attachment must be left open until the SS hardware becomes better defined.

COMPONENT	WT (lb)*	WT (kg)*
Fixed Carrier Structure	1910	867
Deployed Carrier	1280	581
Spool, Enclosure	500	227
Deck-to-Deck Structure	455	207
Cold Plate	115	52
LRM (5)	825	375
Controller	23	10
Circuit Breaker Box	22	10
Other Support Boxes	20	9
LRM Latches	65	29
Plasma Generator (1yr Argon Supply) +	245	111
Tether	3200	1453
Total	8660 lbs	3938 kg

	ICA	DCA
Ixx = Iyy	4021 Slug-Ft2	1344 Slug-Ft2
	5450 kg-m2	1821 kg-m2
Izz	2678 Slug-Ft2	1521 Slug-Ft
	2364 kg-m2	2061 kg-m2

*Includes 15% Contingency
+Add 350 kg (790 Lb.) for 5 yr. supply

Table 3.2-3 Tether Deployer Mass Properties

4.0 OPERATIONAL CONSIDERATIONS

Electrodynamic System Efficiency

The magnetic field study indicated that the orbital variation of the Earth's magnetic field would result in large voltage swings over a single orbit. This has a significant impact on system efficiency and operational scenarios. To help estimate the magnitude of these effects a parametric study of system efficiency was completed. The parameters considered in this study were payload power, tether thermal finish, and system operating voltage.

The tether length and diameter were held constant at 20 km and .927 cm, respectively, for all cases. The converter efficiency was assumed to be 96%. The tether resistance was calculated as a function of tether temperature. The payload power, induced voltage, and tether thermal finish were varied over their expected ranges. System efficiency (power delivered to the SS bus divided by total system power) was then calculated and plotted.

Figures 4.0-1 and 4.0-2 present the results of this study for several typical conditions. Figure 4.0-1 plots system efficiency as a function of payload power for two different tether thermal finishes. The first plot is a metallic type finish with a high ratio of solar absorptance to emittance (i.e. bare metal). The second plot is a second surface aluminized teflon finish with a low absorptance to emittance ratio.

The metallic finish shows a rapid reduction in system efficiency when the induced voltage is low. This is due to the increased tether temperature caused by internal joule heating. The resistance of the tether increases rapidly since the low emittance of the external covering keeps the tether from radiating its heat to space.

The second plot shows that efficiency drops much slower with the high emittance coating on the tether. However, even with this coating, the efficiency falls off rapidly when the induced voltage is less than 5000 volts (as it will be for much of each orbit).

The variation of system efficiency with tether thermal finish is illustrated in the plots of Figure 4.0-2. The first plot shows that the tether thermal finish is not very important for high induced voltages where the currents can be kept low. However, the second plot shows that when the induced voltages are relatively low the tether thermal finish will have a large impact on overall efficiency.

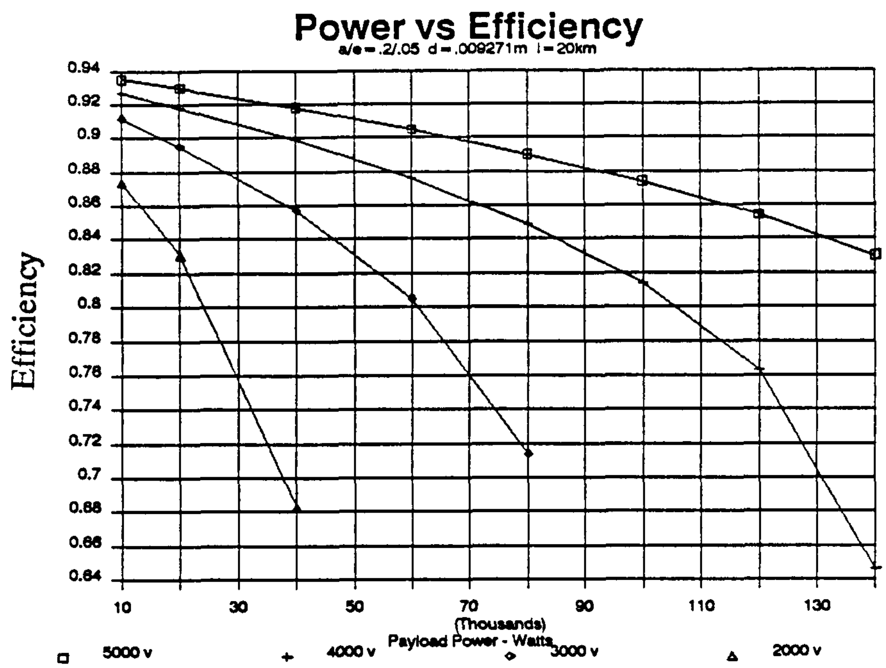
This study has quantified several factors of importance to electrodynamic tether design and operation. For instance, system efficiency will drop quickly when induced tether voltages are lower than the system design voltage. Induced voltage is a factor of the local magnetic field strength and the tether alignment. The magnetic field cannot be controlled, but conceivably the tether alignment could be by appropriate IxB phasing.

Another important consideration should be the external finish on the tether itself. Low absorptance, high emittance, finishes should be used to maintain higher system efficiencies during periods of low induced voltage. This item will need to be balanced against potential materials degradation problems caused by differential expansion and operation at cold temperatures.

Orbit Perturbations

A preliminary assessment of SS orbit perturbations due to ETS operation in a day/night mode has been made using an orbital analysis program. The TRACE orbital dynamics program was used to run multiple orbit runs on a Space Station model with a simulated tether attached. The model assumes that the tether exerts a constant force, relative to the velocity vector, of 25 newtons. The model does not include any atmospheric drag effects. The Space Station is assumed to be in an initial 500 km circular orbit at 28.5 degrees inclination.

Several simple motor/generator scenarios were run to assess the impact on the Space Station (or platform) orbital parameters. The cases run include;



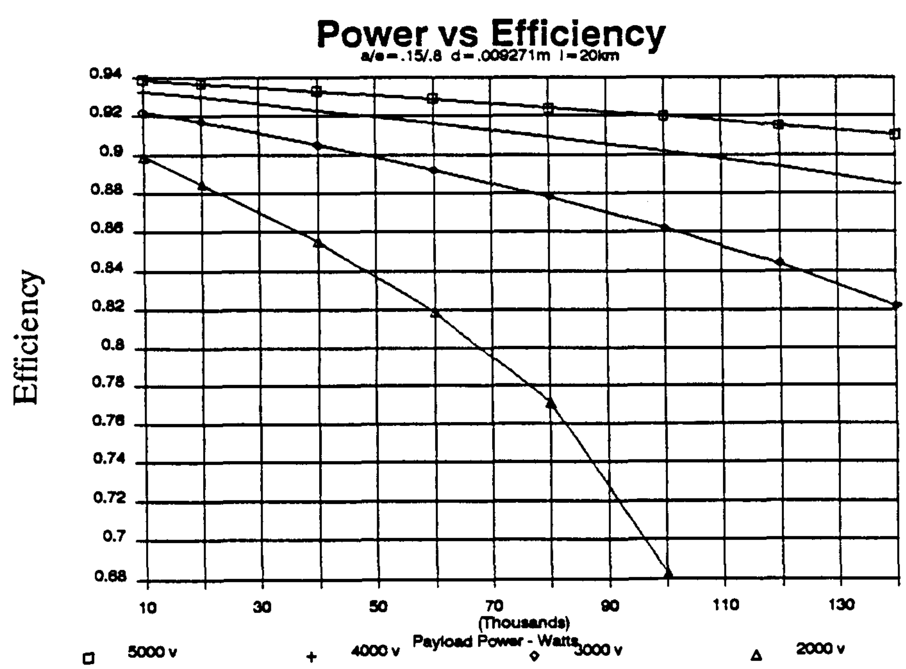
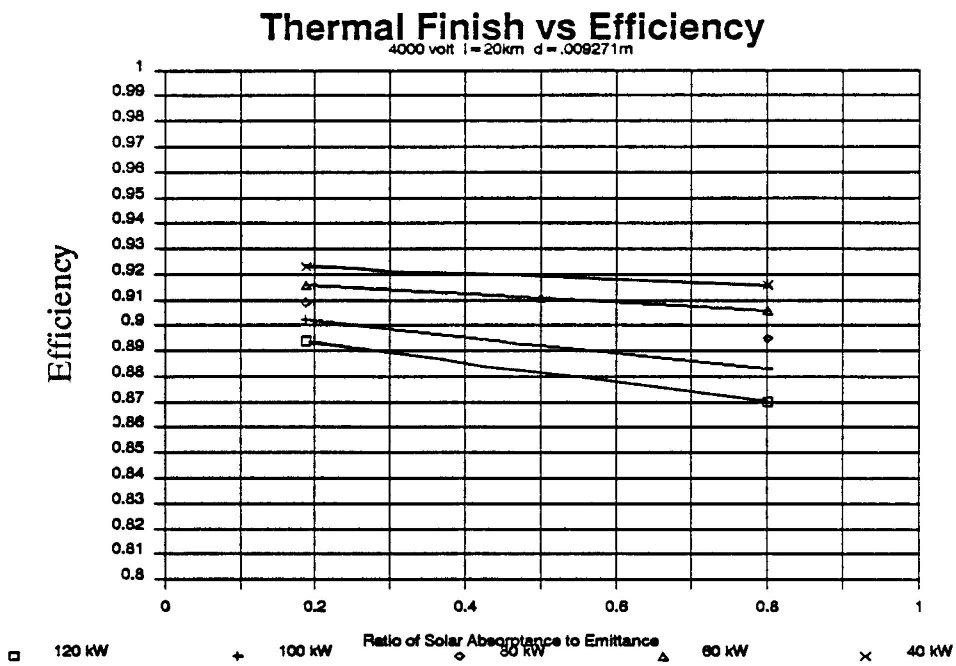


Figure 4.0-1 Tether Power vs Efficiency



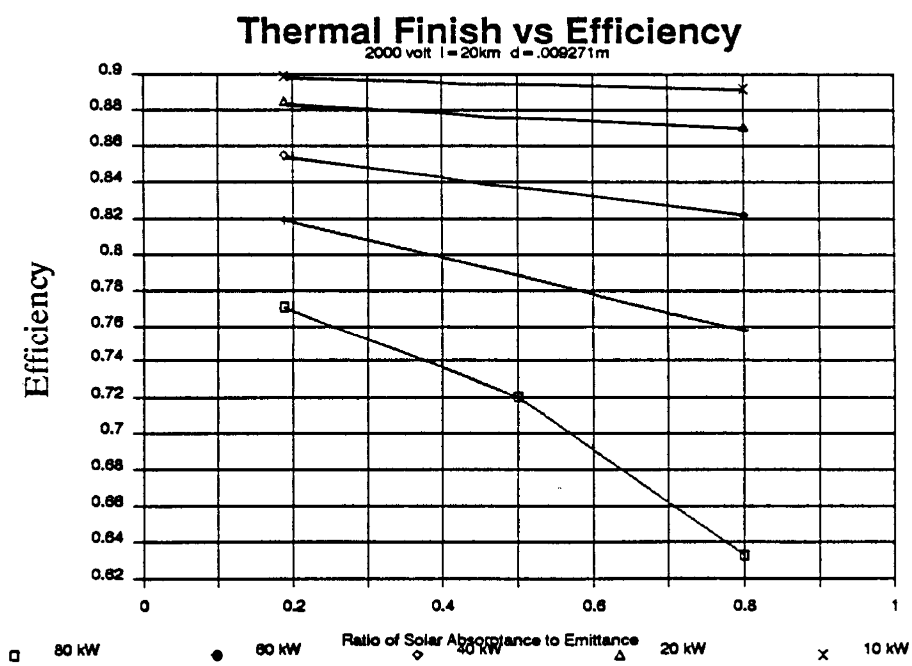


Figure 4.0-2 Thermal Finish vs Efficiency

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OF POOR QUALITY

- 35 minute generator mode followed by a 60 minute motor mode
- 35 minute generator mode followed by a 35 minute motor mode on the opposite side of the orbit
- 35 minute generator mode followed by two 17.5 minute motor modes on opposite sides of the orbit.

The analysis is very preliminary, but all of the runs resulted in significant perturbations to the orbit. The first two cases resulted in an elliptical orbit with perigee being reduced at the rate of approximately .3 to .06 km per orbit (over 7 orbit simulation period). Apogee altitude was increasing at the rate of .87 to .61 km per orbit. The final case resulted in both apogee and perigee increasing.

Some of the orbit perturbation is due to net energy being put into the orbit due to the simplifying assumption of constant thrust. This could be minimized in any future runs by adjusting the motor periods to assure each orbit has the same energy level.

It appears that the IxB phasing for tether libration control may be complicated by the results of this study and the magnetic field study. These studies indicate that a variety of operational constraints may limit the use of IxB phasing for libration control. In addition the cyclical operation of the tether in motor and generator modes will perturb the Space Station orbit. However, the magnitude of the perturbations over the long term (weeks or months) have not been determined.

This preliminary examination indicates a need for more detailed study of this phenomena. Simulation times of many weeks may be necessary to fully envelope the perturbation effects. Future analysis efforts should include simulation of IxB scenarios in addition to the normal day/night current reversals.

IxB Phasing

A part of this study was to examine the operational and performance effects of IxB phasing for libration control. To accomplish this in a quantitative manner several simulation runs using the GTOSS (ver. C3) analysis program were needed. Initial runs with this version indicated computer run times that were larger than real time, which would preclude simulation times on the order of several orbits. A new GTOSS version (D1) includes analysis enhancements that significantly reduce the computer run times. However, this new version was delivered to BASD too late to allow the analysis phases to be completed for this report.

There are a few operational constraints that can be identified without orbital simulations. For instance, it will probably not be practical to place the tether in the motor mode while in the earth's shadow. This is because of the high loads this would place on the SS batteries and or fuel cells. They would have to carry the full SS equipment load plus the tether load. Therefore, IxB phasing strategies that involve reversal of tether current will be restricted to daylight portions of the orbit when excess power is available.

5.0 OPERATIONS

Shuttle Launch

The two ICA's will be mounted in the Shuttle cargo bay as 'typical' payloads, i.e., no special interfacing is required. The ICA uses four Payload Retention Latch Actuators (PRLA) and one Active Keel Actuator (AKA) in the cargo bay for structural interfacing. A Shuttle Umbilical Release System (SURS) connector provides the electrical interface between the shuttle and the ICA. This connection supplies the data and power lines that may be required prior to on-orbit deployment.

Space Station Installation

ICA

The following sequence of events would be used to remove the ICA's from the STS bay and install it on the SS. Note that the ICA's can be delivered to the SS in separate STS flights, if necessary.

- Following the Shuttle docking to the Space Station, any in-bay system tests/checks are performed on the Integrated Carrier Assembly (ICA).
- The Mobile Remote Manipulator System (MRMS) connects with the fixed deck carrier Electrical Flight Grapple Fixture (EFGF) and verifies electrical interface.
- The SURS connector, 4 PRLAs, and the one AKA are actuated, releasing the ICA from the shuttle.
- The MRMS moves to the appropriate Space Station bay (one on the upper boom and one on the lower boom) and places the ICA over the Station Interface Adaptor (SIA).
- The ICA is lowered onto the SIA using the MRMS camera and visual cues to align the FCA alignment pins with the SIA Y-guides.
- The berthing latch, then electrical and fluid drives are activated, providing the SS-ICA structural, electrical, and thermal interfaces. Power and signal for the mechanism drives is provided through the MRMS/Grapple interface.
- Following verification of the fluid, power, and data interface connections, the OMV can be moved into place on one of the ICA's.
- The OMV is berthed with the Deployed Carrier Assembly (DCA).
- The 6 tether launch locks on the spool are fired, releasing the tether restraints.
- Any final system checks are performed.
- The OMV is powered just prior to activating the DDIS separation bolts, allowing the OMV and DCA to slowly back away from the fixed carrier assembly.
- The OMV is maneuvered to back away from the SS in the anti-velocity direction (for the 'upper' tether) at a controlled rate to maintain tether control.
- As the OMV nears the 10 km separation distance from the SS, the rates are slowed until the end of the tether is reached.
- The OMV separates from the DCA and returns to the SS.
- The OMV now attaches to the second ICA system and repeats the deployment scenario.
- Once the ICA tethers have been deployed both plasma generators are activated and IxB phasing is used to damp out any residual motion of the two tethers.
- Normal operations begin.

INTERCONNECT CABLE

The ICA interconnect cable is required to complete the electrical circuit between the upper and lower tethers. The cable will be in place before the ICA's are located. The cable will be routed and attached to the Space Station following typical procedures for Space Station wire routing. However, locations, method of attachment, and installation procedures are not well defined yet for the Space Station.

Normal Operations

OPEN LOOP OPS

Except for periodic tests and checks, there should be no manned operations (open loop) required once the system becomes operational. It is assumed however that there will be a 'break in' period prior to letting the system run on its own where most of the system operations will be performed open loop. The periodic testing will be required to verify the software and hardware status. These open loop operations will be clarified as the hardware and Space Station become better defined.

CLOSED LOOP OPERATIONS

Once the system becomes operational, all systems will be controlled closed loop. This includes the IxB phasing and the plasma contactor operations. The IxB control will be responsible for dampening the tether librations. The IxB phasing will involve switching the converters through the Control Electronics box at the correct time between the power mode and generator mode. Additional signals may be sent to the DCA through the ETS communications system to configure the plasma contactors when changing current direction.

PLASMA CONTACTOR CONTROL

The Plasma Contactor System is a module mounted on the DCA self contained electronics used for regulating the flow of Argon to the Plasma contactor. Signals fed through the tether, or by RF link, to the subsystems module electronics provide the information for the actual control of the gas supply, high voltage circuits, and possibly tether electrical configuration.

Maintenance

FCA Maintenance

No components located on the FCA will require any scheduled maintenance. However, provisions have been made in the FCA design to allow on-orbit replacement of all active components except the tether itself. In particular each FCA carries a spare LRM that can be used to replace a faulty unit. At this time it has not been determined if this "replacement" will be done electrically by the SS Power Source Controllers using by-passes, or if an EVA or robotic replacement will be needed.

DCA Maintenance

Only the plasma contactor gas supply on the DCA shall require periodic servicing. The schedule for Argon supply replenishment is contingent on supply tank volume and flowrate to the contactor. The baseline would require Argon resupply approximately once each year. Further study would show the cost effectiveness of upgrading the tank sizes for a five year or even full life (non refillable) ten year supply. Just prior to Argon depletion, the OMV with a tanker attachment would dock with the DCA and refill the Argon tanks through the fluid interface connection.

Repair

FCA Repair

The mechanisms on the FCA used for docking the carrier to the Space Station are two failure tolerant since limited access precludes any repair operations on them. A 'spare' LRM is provided on the cold plate in the event of a failure of one of the operating four. Each LRM interfaces to the cold plate through a latching mechanism. This mechanism allows for EVA removal and installation of each separate LRM. The mechanism provides the mechanical and electrical interface and can be activated by an EVA astronaut using only one hand. Other components on the FCA are generally EVA accessible for any contingency repair of other hardware.

It would be very desirable to provide an electrical means of switching out a defective LRM. This would involve high current, high voltage Remote Bus Isolators (RBI) units. These devices are being developed for the Space Station, but may not handle the tether voltage levels. Maybe these can be modified for use with the tether system.

Tether Repair

Depending on its final configuration, a damaged tether may be repairable by using a robotic device deployed from the FCA. The device would 'crawl' along the tether until it sensed a damaged area, repair the area, and continue along until it sensed another damaged area. This type of hardware would only be feasible for repair of superficial, i.e. non-structural damage to the insulation caused by a micro-meteoroid for example. Structural damage would require either much more elaborate hardware on the crawler or a different approach to repairing the tether.

Two other options for dealing with a damaged tether seem viable; either replace the entire tether after a period of time when the tether starts loosing efficiency due to the damaged areas, or replace a section or splice out the damaged area. Either scenario requires elaborate EVA and/or OMV procedures however. A broken (severed) tether has much more serious consequences. Of course, the flow of power is interrupted, but also the DCA immediately starts to drift into a different orbit.

For the upper tether, the break defines the perigee of the new orbit. The apogee will occur half an orbit later and have an increased altitude of about 7 times the tether length (i.e. 70 km). For the lower tether, the break defines the new orbit apogee, and the perigee will be at a decreased altitude of about 7 times the tether length. Aerodynamic drag on the DCA of the lower tether will probably require quick action if the intention is to recover the DCA before it re-enters the atmosphere.

In the event of a break, some options are to A) locate and retrieve the ends of the tether so that they can be rejoined, B) locate and retrieve the Deployed Carrier Assembly (DCA) back to the Space Station, or C) replace the DCA and tether.

Option A would require the development of currently non-existent hardware. The hardware would have to be capable of grabbing the end of the tether and splicing the two ends with full mechanical and electrical integrity. The hardware would probably be mounted to the OMV which would be used to search for the end and then tow the tether/DCA to the other tether end. This approach is probably not practical from an implementation standpoint given the current development status of robotics for the SS.

Option B, although more feasible, is still not practical enough to consider seriously. As presently configured, for minimal up-front costs, the DCA would have little value if it was recovered since there is no means to replace the tether onto the DCA spool. The alternative is to invest more up-front costs in a configuration that would allow SS servicing following a tether break.

The options could include a spool that would be easily dismounted and handled, or switching to a reel system. A replaceable spool would be the simplest approach, although FSE would have to be developed to carry up a new spool and tether. A reel system similar to the TSS hardware with reel motor, level wind, and tension control system, opens up some more options. The reel system could retrieve the remaining deployed section of a broken tether, but the other tether piece would have to be severed. Once the DCA is retrieved and the joint spliced (by EVA), the system could be redeployed and made operational, although at a reduced capacity because of the shorter length. Obviously with this approach the location of the break will have a major impact on the system capacity after redeployment. Although the reel system could be mounted on either the DCA or FCA, the FCA would have the advantage of having Space Station power available for the reel-in operation.

An alternative, at the expense of weight and cost, would be to supply reels on both the DCA and FCA so that both tether sections could be retrieved, allowing the system to return to full capability after splicing. Regardless of approach of spool or reel, the feasibility of retrieving the DCA from a new orbit back to the Space Station is still at issue. Also, the reels would mean running the tether current through high voltage slip ring assemblies, possibly at both ends. This would increase cost, complexity, and reduce reliability of the electrical path.

Option C, replacing the errant DCA, avoids the problem of recovering the DCA. It does however, have a greater cost impact, sparing a DCA with tether, spool, plasma generator, and structure, versus sparing only a spool and tether. Splicing the tether or reconnecting the end to the FCA circuit box still has to be addressed regardless of which approach would be taken. Just the safety and operational issues to contend with here are formidable. On-orbit experience gained from other tether systems will be invaluable in predicting tether life (i.e. likelihood of micro-meteorite impact, AO degradation, etc...) and handling requirements so that more intelligent decisions can be made on the servicing approach to the electrodynamic tether system.

DCA Repair

For all practical purposes, repair operations performed on the DCA are limited to the OMV capabilities once the system becomes operational since there is no other means to access the hardware. Studies are developing mechanisms and add on robotics for the OMV to enhance its on orbit repair capability, but there will probably be limited hardware development for these systems in the near future. The active systems on the DCA will be redundant to increase the probability of meeting the ETS operational life goals.

Retirement

The Electrodynamic Tether System will have unique disposal requirements placed on the hardware because of the concerns of releasing a deployed tether as space debris.

Therefore, a plan should be developed to retrieve the deployed systems at the time they outlive their usefulness. Since the baseline system does not have a reel-in capability, a simple reeler would be developed that could be attached to the FCA. The reeler would simply start to wind up the deployed tether at a slow rate until the DCA approached a minimum safe distance to the Space Station. At this time the OMV would dock with the DCA to provide control during the final winding of the tether. The FCA, DCA, and reeled-up tether could be transported back to earth in the STS, or possibly de-orbited to burn-up in the atmosphere.

6.0 SAFETY

From the design standpoint, the system must be free from electrical breakdown and arcing caused by outgassing, plasma effects, and spacecraft charging. NASA SP208, "The Prevention of Electrical Breakdown in Spacecraft" should be used as a design guide.

Further, the system must be designed to assure safety of the Space Station and crew. Therefore, the design will be in accordance with NASA JSC-11123, "STS Payload Safety Guidelines Handbook", Sec. 3.4 Electrical Subsystems, and NASA MSFC-STD-512, "Man/System Requirements for Weightless Environments," Sec. 3.5 Safety. Table 6.0-1 is a listing of the primary safety considerations for operations in a manned environment.[17]

In addition the electrodynamic tether system (ETS) shall conform to JSC 30000, Section 3, Para. 2.1.11 of the Space Station Design Requirements document. This is a general standard and detailed safety guidelines will have to be developed for the tether system. The lessons learned from operating the Tethered Satellite System (TSS) in the near future can be adapted to the ETS in the areas of safety and tether dynamics. Use of high voltages on the manned Space Station (and possibly on the Orbiter during developmental testing) is probably the safety issue of greatest concern.

The major problems are shorting to ground that would endanger the crew and Space Station electronics, and proximity operations near the high voltage tether system. This may involve the MRMS or MMU outfitted astronaut servicing a nearly payload, or even the shuttle maneuvering in the immediate area. It would be easy to agree that the system should be disabled (DCA plasma contactors switched off) when an LRM on the tether system is being serviced for example. It is more difficult to decide what proximity is allowable or what safety measures should be taken when servicing a nearby payload. These safety guidelines are to be developed and refined as the hardware design and operations scenarios mature.

- Safety is a non-tradeable consideration in the design. No single failure or credible combination of failures shall result in injury to crew or damage to other equipment.
- The system shall incorporate redundant control and monitoring circuits. These shall employ independent, redundant power sources.
- System design shall provide positive power removal capability before disconnecting and reconnecting modules/components.
- Plugs, receptacles and fluid lines shall be keyed or physically restrained, etc., so that it is physically impossible to mismate them.
- Circuitry having capacitor output stages shall be provided with bleeddown circuits.
- Equipment cases shall be at ground potential to prevent possibility of shock hazard to personnel or shorting to ground by conductive debris or liquid leakage.
- Materials employed for insulation, circuit boards, barrier strips, coatings, etc., shall not out gas toxic vapors or present flammability hazards under both normal and abnormal operating conditions.

Table 6.0-1 Safety Criteria

Design Impact

Mechanical

The ETS mechanisms should be designed to be two-failure tolerant. The DDIS separation system and all actuators will be two failure tolerant. The LRM latching hardware will be configured so as not to require the astronaut to input any loads on the boxes during EVA servicing operations. The plasma contactor high pressure Argon tanks will be enclosed in secondary structure for impact protection. The grapple fixture and berthing latch on the Deployed Carrier Assembly are provided to aid in handling and allow a secure berthing in the event that servicing is required.

Electrical

All electrical boxes and cabling used on the tether system shall conform to the shuttle and Space Station safety documents. The unique power handling requirement for this hardware will require the generation of additional safety guidelines for the ETS operations. Any electrical failure of the tether system must not render the Space Station power system inoperable. The hardware/software design will incorporate a back-up mode to allow degraded operation until repairs are made. This may require that plasma contactors be added to the FCA's. Any ETS failure will not cause a life threatening situation for the crew or station.

Due to the high voltages generated by the system, insulation breakdown and arcing are concerns within the vicinity of the SS where gaseous debris (i.e. a partial atmosphere) may develop. For this reason it may be desirable to increase the tether insulation protection in the Space Station proximity (50-100 m) to lessen the risk of contact by astronaut, OMV, etc... This could be implemented by an EVA procedure to install a protective sleeve around the tether. This sleeve might extend a few tens of meters to a few hundred meters. This sleeve could supply mechanical and electrical protection for the tether.

Operations Impact

Broken Tether

According to a TSS study[18], the reaction of the tether at the time of a break is dependent on the elastic and damping properties of the tether, its tension, length, and relative location of the break. Depending on these values, a break may cause the tether to initially recoil towards the Space Station, but gravity gradient forces dominate before the recoil is complete and pull the tether taut again. This would most likely occur with a break near the deployed end of the tether, leaving a large tether mass for the gravity gradient force to act on. Relatively low tensions keep the recoil forces small, and high damping characteristics within the metal tether absorb and dampen the tether motion. This type of break should pose no hazard to the Space Station. The Deployed Carrier Assembly would move to a different orbit from the Space Station, and the broken tether end would remain in a deployed (albeit wandering) state.

A different situation results from a close in break. The recoil forces are now greater that the gravity gradient forces and the tether could impinge on the SS. A computer model, such as the Smithsonian Astrophysical Observatory (SAO) SLACK program or GTOSS, can be used to determine what the results might be for various break situations. An important factor in the modeling is the tether damping characteristics. These will probably have to be measured on a tether prototype.

A safety concern remains as long as there is a possibility of the tether recoiling onto the SS. Not only is it impossible to predict the location of a break and so its reaction, but the mass of the SS precludes any collision avoidance maneuvers with only a few seconds of reaction time. The SLACK model predicts however, that there may be some advantage to severing the tether, while it is still under tension, at the SS end. This would require developing a detection device that does not depend on tension to sense a break (a current sensor would work while the tether was operating). The tension wave travels about 3 Km/sec, so there is very little time to analyze the situation.

Another approach is to use stiffening devices to keep the tether from impacting the SS. If a protective housing is installed around the tether in the vicinity of the SS, it could be used to prevent the broken tether from impacting the SS. The required length of tether that would have to be stiffened would have to be determined by analysis. An analysis similar to the SAO TSAT analysis should be completed for the ETS tether. This type of analysis would provide a preliminary estimate of the recoil hazard of this concept.

Tether Deployment

The rate and position of the Deployed Carrier Assembly will be controlled by the OMV during tether deployment. However, there are failure modes that need to be considered. If a jam in the spool occurs during the maximum deployment rate, the inertia of the OMV/DCA system might stress the tether beyond its limits, resulting in a broken tether recoiling towards the Space Station or over stressing of the SS structure. As the deployment rates can be slow, a maximum rate could be set based on planning for this kind of event. The OMV dynamics, following a failure while attached to the SS by a tether, is an important safety issue. The tether guillotine at the FCA may solve this concern. Safety guidelines developed for the OMV and Space Station will address the safety issues dealing with mating the OMV to a payload.

On-Orbit Operations

After the system becomes operational, the tether will experience in-plane and out-of-plane librations. This in itself is not a safety concern except for proximity operations (MRMS or EVA) or nearby payloads that must be aware of a potential high voltage hazard and the motion of the tether. This will probably result in the establishment of an 'exclusion zone' around the deployed tether.

The current switching through the tether to change from motor mode to generator mode that takes place every orbit will be a closed-loop operation. However, a malfunction of this operation could adversely affect the SS power system, impart attitude perturbations into the SS, or cause the tether tension to approach unstable conditions. Therefore, careful planning and testing of the ETS control software will be necessary. The unstable conditions will develop slowly so automatic warning systems should be easy to implement. Most corrective actions can probably be crew initiated with automatic controls only used in extreme conditions.

Servicing

All hardware will conform to the safety guidelines to be established for Space Station payloads that require servicing by EVA and/or robotics. This will include the elimination of sharp corners and protrusions, placement of handholds in conspicuous locations, and reactionless equipment hold-downs. Specific safety guidelines will have to be developed for EVA (and MRMS) servicing of an operational tether system so servicing, such as LRM box changeout, can be done in a 'routine' and safe manner. A zero current, zero voltage condition at the tether will probably be necessary and verifiable prior to any servicing activity. This may necessitate the addition of a plasma contactor at the FCA to assure that the local potential is brought to zero.

Safety Issues

Following is a summary of the major safety issues that will need to be addressed further.

- Sufficient voltage standoff to prevent shorting to ground.
- Isolation of the high voltage tether from SS contaminants to prevent coronal breakdown and arcing.
- Operational response to a broken tether for responding to tether recoil towards the Space Station.
- Misguidance of OMV during deployment of DCA could result in over stressing of tether and/or adversely affecting the Space Station attitude.
- Improper switching of current flow (motor mode vs. generator mode) could adversely affect the SS power system and/or impart attitude perturbations due to large misalignment between tether line-of-action and SS CG.

Disposal of broken or old tethers and determination of their possible impact on the orbital debris environment.

7.0 DEVELOPMENT TEST & DEMONSTRATION

The experience gained during this design effort has resulted in the identification of three major areas where demonstration experiments and/or additional development will be helpful to the ETS program. These three areas are high power electrical systems, tether system dynamics, and logistics. The following paragraphs describe the major technology areas where development activities will be beneficial. These technologies are not specific to electrodynamic tethers and much of the development and testing has already been proposed, or is being pursued, to support other space and commercial requirements.

The electrical systems development requirements are mainly in the area of component technology. This includes solid state components, magnetics, and capacitors. Solid state devices for controlling power in high current and voltage environments are just now becoming available. Much of the past development in this area was performed to satisfy ground based commercial interests, not space applications. However, advanced development has begun for electrical components needed to support the Space Station power system. These components should be sufficient to construct the 100 kW demonstration system described in this report. Larger electrodynamic tether systems may need additional electrical component development to support higher currents and voltages.

The hollow cathode plasma contactors are primary components in the ETS concept and characterizing their performance in the space environment is a prerequisite to detailed system design. This characterization needs to be accomplished early in the ETS development phase.

Tether dynamics is an area where demonstrations are crucial to the continued development of the ETS concept. Efficient operation of the ETS will depend on careful control of the tether motion under the influence of the electrodynamic forces. Early information in this area will be available from the T-SAT program and, hopefully, from proposed Shuttle experiments. Also, many of the safety questions cannot be fully addressed until a reliable and verified means of predicting tether response to disturbances is developed.

The logistics of ETS operation contains many design and implementation challenges in terms of maintenance and repair during the ETS operational life, and disposal of the tether and its associated subsystems at the end of their useful lifetimes. Development and demonstration in the areas of low maintenance materials, robotics, orbital re-supply, reliability analysis and prediction techniques, safety, and orbital debris prediction and control are needed. These same items are already the subject of Space Station advanced development activities, therefore, only items specific to the ETS concept will need further attention.

The required development and/or demonstration programs can be divided into categories depending on the 'environment' required to accomplish the objectives. One category involves development tests and demonstrations that can be accomplished in ground facilities. This group includes some items in electrical systems and tether system logistics.

Another category is tests and demonstrations that require the space environment for validity. In the early development stages these types are primarily in the tether dynamics and plasma contactor operations areas. However, as the design matures additional space testing will be required.

Finally, some items are in both areas because portions of the work can be done in ground based facilities, but part of it must be accomplished in space.

The approach to development and/or demonstration programs should be to address those items that can be effectively pursed in ground facilities first, since they will probably be less costly. However, early development and demonstration consideration should be given to key technology questions (i.e. plasma contactor operation, space plasma impedance, and tether dynamics) even though they require space demonstrations. A clear understanding of these areas is needed before the ETS design can proceed.

Many factors must be considered to determine a logical progression for the development/demonstration program. Some of the considerations include: test environment, required facilities, technology overlap with other development programs, importance of the technology to the viability of the ETS concept, and the anticipated costs.

If the required or preferred test environment is space the mode of transportation becomes important for scheduling and cost considerations. The Shuttle schedule is full for many years in the future and some of the ETS demonstrations may have Shuttle safety impacts requiring careful, detailed, costly, and time consuming analysis and certification procedures. This will probably result in delaying any demonstrations or tests requiring the Shuttle. The Expendable Launch Vehicles (ELV) may present a better schedule and economic choice for the near future and should be considered when flight demonstration requirements allow.

Ground based tests and demonstrations are very desireable because they are less costly and easier to schedule. Therefore, testing and demonstrations that can be accomplished, or started, in ground facilities should be given early consideration.

Space Station advanced development activities augment and support the ETS in many areas including: solid state component technology, power utility controls, high power system testing, high power magnetics and capacitors, and materials development. This information will be used to the fullest extent possible. Those areas of the ETS development program that may be effected by the results of these studies will be scheduled to make maximum use of this information. The Space Station advanced development program office should be kept informed of the ETS needs, where they differ from SS needs.

Slight modifications to component specifications and testing may allow parallel development of Space Station and ETS components. This will result in a minimum cost development approach.

It is obvious that the fundamental ETS technologies should be developed and demonstrated first. Ground based activity in the key areas of tether dynamics and hollow cathode characterization have been proceeding for several years. However, these areas have reached the point where space demonstrations are needed. Several experiments have been proposed and some are in advanced stages of development. The characterization of the space plasma is another candidate for early development efforts. An accurate mathematical model of the plasma contactor interaction with the space plasma, at high current levels, will be needed to complete the design of control circuits and algorithms for managing tether power and motion.

A reduced size ETS test bed system is recommended before demonstration of the full-scale 100 kW system. The smaller system would be used to fully characterize the operation of the system and allow verification and tuning of simulations used to design the full-scale system. The test bed will be a space based system and could be small enough for an ELV launch. The actual size required for the ETS test bed will be a function of cost, schedule, launch capability, and inputs from the science community. The system will have to be large enough to test and confirm the mathematical models over a range adequate to confidently predict the operation and success of the full-scale system. Small systems of this type are already under study in the US[19] and foreign[20,21] countries.

Based on the above considerations the following specific development and demonstration activities are regarded as important to the ETS concept. Some of these areas are already under development for programs other than electrodynamic tethers, but are included for reference. They are presented in a logical order from the ETS development requirements standpoint, but do not include scheduling constraints.

1) The following electrical component development areas are considered important to growth of the ETS beyond the 100 to 200 kW level.

- Development of fast switching high power semiconductors. Ideally these would be bilateral conduction devices controlled directly from logic circuitry. Bilateral conduction would eliminate need for separate rectifiers in the converter module.
- Improved semiconductor packaging for space environment including better hermetic sealing and improved thermal interfacing of chip to package.
- Improved magnetic core materials for high frequency transformers and inductors.

As stated earlier much of this development work will be accomplished under the Space Station advanced development program. The DOD is also doing development work in this area to support their programs.

2) Build a set of converters that will use standard components and operate at a reduced power level. These units will be used to test and develop the interface between the SS power system and the ETS. These tests will establish the ability of the SS Power Source Controllers to control the operation of the ETS converters in both the motor and generator modes.

A full set of eight converters should eventually be built so that synchronization control of the units by the PSC can be fully evaluated. However, a smaller set of two to four should be developed initially to verify the design approach. This smaller set could also be used to establish the feasibility of using the PMAD hardware to accomplish the converter control functions. This same set of converters can be used in a parallel configuration to test the operation of the system in the proposed growth configuration.

Algorithms (software) for the ETS IxB libration operations could be tested and developed with the small converter compliment. This would allow early detection and correction of problem areas in implementation of the control algorithms. This testing could also help establish the correct compliment of sensors for ETS end mass state vector determination.

Testing of procedures during simulated converter and control failures could be completed with these development converters. Any problems with bypassing converters and reconfiguring the system after a failure could be determined and design corrections made. The system would also be beneficial in development and testing of appropriately modified Remote Bus Isolators for this application. However, the power level would have to be increased to operational levels for this development testing.

Since the design of the ETS converters is almost identical to the SS PMAD, it may be possible to use the same hardware for ETS development testing. At the very least, the same components could be used to construct the ETS converters.

3) Study fast bi-directional switching of ETS converters operating with a SS PMAD type system. Especially the sustained reverse power operation that will be required for interfacing the ETS in the motor mode should be experimentally demonstrated. This testing can be completed using the LeRC facilities being built for SS power system development. This experimental system can also be used to develop and electrically test converter control strategies.

4) Development of shielding and design techniques for EMI/EMC of high voltage and current systems operating in space. This will be addressed by the SS community for the PMAD architecture, but at much lower voltage levels than the ETS system. Therefore, additional design effort will be required for the ETS to meet the EMI/EMC standards for the SS.

5) Study of the dynamics of a tether that is deployed from the end of a spool, as proposed in the baseline concept presented earlier in this report. This concept is similar to the Small Expendable Deployment System (SEDS) concept under study by MSFC and their contractors. However, the tether that will be deployed for ETS will be larger and stiffer than the SEDS tether because of the construction. Therefore, additional analysis and testing will be needed to determine the correct tether design to allow this type of deployment for the ETS. The primary concerns will be binding of the tether and residual bending in the deployed tether. These concerns can probably only be resolved through a test program involving simulated deployments using ETS equivalent tethers. This testing would ideally be done in the zero g environment of space, but it may be possible to design experiments that can be accomplished in ground facilities.

6) Recoil analysis of a broken tether needs to be completed to aid in the design of the ETS. This analysis is necessary because of the safety consequences of a severed tether impacting the SS. Additional hardware may be necessary to prevent the tether from contacting the SS structure following a structural failure in the tether. This analysis could probably be accomplished using the GTOSS program once the elastic properties of the ETS tether are determined. The determination of these properties should be made a prime activity once the appropriate materials have been selected for its construction. It may be possible to measure the elastic properties of the tether in ground facilities once a sample length of the tether is constructed. The minimum length that needs to be constructed for this determination needs to be analyzed.

7) Detailed analysis and simulation of the dynamics of the tether and end mass under power and during storage or non-use modes. Stability in the yaw direction (i.e. rotation about the local vertical) has been assumed in our design, but may not be realistic. If the end mass is unstable in yaw an attitude control system would need to be added to the design. Yaw stability is required if OMV docking with the end mass is assumed. Rotation in the yaw direc-

tion may also effect operation of the plasma contactors, although there is currently no evidence of this.

8) Construction on a small ETS system for deployment from the STS or possibly an ELV would make a good demonstration of the system. This system should be sized to provide a reasonable scaling to the full ETS configuration. The main objective of the mission would be to demonstrate:

- deployment dynamics of a tethered system without the benefits of a reeling system.
- operation of plasma contactors at a current level approaching that of the full ETS system.
- synchronization and control of multiple converters with a single controller of SS design heritage.
- evaluation of the effectiveness of IxB libration control strategies.
- verification of the control algorithms for day/night operation of the system in an energy storage/retrieval mode.
- study effects on the operation and efficiency of the system in the presence of small defects (micrometeoroid penetrations) in the tether insulation. These defects may be natural or deliberately introduced for the purposes of the experiment.
- test theories about the operation of plasma contactors.
- study the EMI characteristics of the tether and plasma contactors under operational conditions.
- characterization of the plasma impedance between the two plasma contactors.
- determine the effect of obstructions in the vicinity of the plasma cloud on plasma contactor performance.

9) Development in the area of high voltage, high current disconnects for space applications. This work is necessary if on-orbit repair and servicing operations are to be possible for the ETS. These connections have to be able to be made remotely or by EVA. The resulting connection must have a low electrical resistance and provide a good layer of insulation to prevent coronal breakdown and arcing in the SS environment. The connection must also provide effective EMI shielding and possibly a good thermal interface if cooling is required. Initial development in this area will probably be done under Space Station advanced development activites using ground facilities. Final development and test will require a manned space environment like the Shuttle or Space Station.

10) Tether insulation material evaluation in terms of life expectancy, AO degradation, high energy particle exposure, UV, micrometeoroid, thermal cycling and synergistic effects. The SS advanced development program is currently examining many materials for SS use and the tether insulation will be identified from these materials.

11) Develop techniques and devices necessary to service and repair the ETS system. This effort will benefit greatly from the SS advanced development efforts. However, the ETS maintenance environment includes high voltage and a large exposed surface area. This research will eventually require space-based testing, but initial demonstrations and development can start with ground based programs. The techniques and devices necessary for repair and servicing can be developed in ground facilities, however some of the testing will require the zero-g environment of space and probably a manned facility like the Shuttle or Space Station.

8.0 PRELIMINARY COST ESTIMATES

An estimate of the Electrodynamic Tether System hardware costs has been made. This estimate uses cost information generated during a previous tether study[22] and preliminary Space Station hardware costing data.

The following cost data assumes that certain items are GFE. These items include; plasma contactors and support electronics, SS PMAD converters, SS Bus Interface Units, SS Power

Source Controllers, SS integration and support, OMV usage for deployment and servicing, STS transportation to orbit and STS integration.

Space Station common equipment is priced at recurring levels with estimated adjustments for any required modifications. New component costs are estimated by weight using the results from RCA PRICE runs for similar components from the previously referenced tether study. The results of this costing exercise are presented in Table 8.0-1. Following is a list of definitions used in the costing effort.

Estimating Definitions

Engineering Costs

The total cost of design and development engineering including; design engineering, development engineering, normal laboratory experimental work, breadboarding and testing, specification design, manufacturing drawings, data lists, spares lists, prototype material and all other documentation needed for manufacturing and subcontracting.

Manufacturing Costs:

All costs associated with the fabrication of system hardware. These include costs for facilities, support equipment, and the fabrication of the hardware itself.

Integration & Test:

Those costs attributable to the effort of integrating subsystems to the system level and testing them at the system level. Includes costs for engineering design of the I&T process itself (i.e., plan) for both hardware and software.

Ground Support Equipment:

All costs associated with the fabrication and test of GSE used in production, during operations, and for support. Included are materials and labor.

Software:

All costs associated with the development, coding, testing, debugging, and documentation of all software to support the hardware mission. Included are both applications and support software.

Electrodynamic Tether Hardware Definitions

Honeycomb Decks:

Main support structure for the Deployed Carrier Assembly (DCA) and the Fixed Carrier Assembly (FCA). This item includes special inserts for attaching equipment and any modifications for load distribution. These items are assumed to be of the same basic design and construction as those proposed for use by Space Station (SS) Payload Attach Equipment (PAE).

Grapple Fixture:

Standard grappling device used to allow attachment of the payload to robotic appendages such as the STS Remote Manipulator System (RMS) and the SS Mobile RMS (MRMS). These devices are purchased items.

Trunnions:

Standard STS attachment devices. A total of six will be required per Integrated Carrier Assembly (ICA). Four will be sill attachments and two will be keel attachments. Pricing will be based on costs from past BASD programs using the same type of trunnion fittings.

SS Interface:

This is the standard power, data, structural, and thermal interface between the FCA and the SS. This item is priced from information generated during the BASD SS conceptual study for attached payload support. This item includes the cost of developing unique software for the basic ETS data and control interface with the SS.

Deck-to-Deck Interface:

This is the hardware required to connect the DCA and FCA during the STS launch. It in-

Cost Item	Eng.($K)	Mfg($K)	Tot.($K)
Honeycomb Decks	3084	720	3804
Grapple Fixture	**	336	336
Trunnions	313	116	429
SS Interface	5998	1760	7758
Deck-to-Deck Interface	1015	240	1255
DCA/OMV/SS Interface	1242	410	1652
Gas Supply Tanks	**	660	660
Current Converters (5 units)	2012	1010	3022
DCA Power System	**	690	690
Command, Comm. & Data Handling	683	238	921
Electrical Harness	160	40	200
Spool and Enclosure	745	276	1021
Tether	**	350	350
Mechanical Circuit Breaker	243	85	328
Thermal Coldplate	622	134	756
Thermal Control	152	181	333
Converter Control Electronics	550	250	800
Tether Guillotine	62	53	115
Software	2500	---	2500
GSE	2000	500	2500
Integration and Test	2975	1275	4250
Cost of 1st Integrated Carrier Assy.	24,356	9,324	33,680
Cost of 2nd Integrated Carrier Assy.	-	9,324	9,324
Total Cost			43,004*

* Excludes costs for plasma contactors and control electronics, PMAD converters, SS Bus Interface Units, STS integration and launch, SS integration and support, all servicing and repair items and OMV usage for deployment.
**Purchased Items

Table 8.0-1 Cost Estimate

cludes the separation devices (explosive bolts) and associated wiring. This item is costed from RCA PRICE estimates of similar hardware using a mass ratio for cost scaling.

DCA/OMV/SS Interface:

This is the attachment hardware used by the OMV for initial deployment and possibly recovery. The same interface is compatible with the SS mechanical interface to allow the DCA to be temporarily stowed on the SS. This hardware is identical to the MMS FSS berthing platform hardware. Cost estimates for this device are taken from RCA PRICE data from a previous BASD tether study.

DCA Attitude Control:

This subsystem may be necessary to keep the DCA from rotating about the tether line of action due to unbalanced drag and tether forces. The magnitude of these forces have not been determined and so the need for this system has not been definitely determined. Therefore, it is included here as a place marker pending further analysis of the dynamics of this system. No cost estimate is made for this system.

Gas Supply Tanks:

These are the tanks that will contain the gas supply for the plasma contactors. The tanks are assumed to be sized for a five year mission using Argon. The cost estimate includes valves, regulators, filters and lines to connect the tanks to the plasma contactors. These will be purchased items and their costs are extrapolated from similar space qualified equipment flown on BASD spacecraft.

Current Converters:

These are the devices that control the tether current and voltage during the motor and generator modes. The cost estimates are based on RCA PRICE data for electronic boxes generated on a previous tether study. The data was adjusted using a mass ratio for this application. The costs predicted for these items may be significantly in error due to the high voltage, high current nature of the devices. Component technology for these type of devices is just now being developed by NASA LeRC and is assumed to be available for this project.

DCA Power System:

This includes the components necessary to operate the plasma contactor controls and DCA subsystems when the tether is not operating. It is assumed that the tether will supply necessary operating power when it is operating. The components necessary to tap the power from the tether are assumed to be GFE. Cost figures are based on mass weighted adjustments to RCA PRICE estimates for similar components.

Command, Communications and Data Handling:

This is the equipment necessary to communicate commands and data between the DCA, FCA and the SS data interface. The performance requirements for this system has not been definitely established, however for costing purposes it is assumed to be about 30% the capability (and cost) of a spacecraft system to accomplish the same functions. The cost estimate for the spacecraft systems is based on previous BASD satellite programs and information generated by RCA PRICE for the previous tether study.

Electrical Harness:

Required wiring for subsystems and the high voltage, high current tether system. Cost estimate based on mass weighting of RCA PRICE cost estimated from previous tether study.

Spool and Enclosure:

This is the mechanical structure for containing the tether during launch. This item includes launch retention devices for the tether. Cost estimate is based on weight from RCA PRICE model information.

Tether:

Electrical conductor, electrical insulation, thermal control finish, environmental protection coatings, and all hardware required to attach the tether to the FCA and DCA. The cost estimate is based on the best available information, but increased definition in the areas of serviceability, safety, EMI/EMC, and the orbital debris environment could significantly effect the cost of this item.

Mechanical Circuit Breakers:

These devices will be used to remove the high voltage from the FCA during maintenance activities and emergencies. Cost is based on weight using RCA PRICE information for mechanical devices. Not included in this cost is a plasma contactor and associated equipment that will be used to bring the SS end of the tether to local plasma ground before opening or closing the circuit breaker. This equipment is assumed to be GFE.

Thermal Cold Plate:

This is the thermal control for the converters and associated FCA equipment. It is assumed to be of a common design with other SS coldplates. Only recurring costs are used with the assumption being that development costs will be incurred under SS advanced development. Fluid pumping and control is included in the cost estimate.

Thermal Control:

This includes MLI blankets, heaters, and special coatings required to maintain DCA and FCA components within allowable temperature ranges. This items includes costs associated with analysis, design, manufacture and installation of the thermal control devices and materials.

Converter Control Box:

This electronics box will control the operation of the converters during the motor and generator modes. The synchronization of the converters and required motor mode regulation is accomplished by this unit. It also controls the logic to switch converters in and out of the system for fault isolation and recovery. This device will interface with the SS power data bus and be under its control. Cost estimates are scaled by weight based on RCA PRICE data generated for similar electronics boxes. It may be possible to use SS developed equipment for this function which would lower the cost estimate considerably.

Tether Guillotine:

This device is attached to the FCA to allow the tether to be cut lose in the event of an emergency. Cost is estimated from RCA PRICE data.

9.0 CONCLUSIONS & RECOMMENDATIONS

1) Electrodynamic tether simulations should employ at least a shifted and tilted dipole model for the Earth's magnetic field. The IGRF 10th order field should be used, if possible. The latter is especially desireable for simulations involving IxB phasing since the direction of the magnetic field varies considerably from the simpler models in the South Atlantic anomaly.

2) The Electrodynamic Tether System can make use of many components being developed for the Space Station. The PMAD system components can be adapted for use in the control and power handling functions. The test facilities being built for SS can be used for testing ETS components. This testing can be accomplished in conjunction with PMAD development for interface verification, and independently for ETS component development. The facilities being build at NASA Lewis Research Center (LeRC) to support SS power system development should be ideal for testing ETS hardware and software. Coordination of this effort with LeRC should start as early as possible so that ETS development activity can be structured to fit with the LeRC schedule.

3) Tether converters are operated in series with faulty modules being switched out of the circuit with a bypass. This should be studied further when the design of the SS RBI's are finalized to allow for re-design of the circuit. It would be desireable to have the ETS reconfigure itself when a faulty converter was detected. This would involve bypassing the faulty converter and simultaneously switching the FCA "spare" converter into the circuit. This would allow continued full operational capability in the event of a single failure. An ad-

ditional failure on the same FCA would result in a module being bypassed (leaving three in the circuit) and an increased voltage drop across each of the remaining converters. However, it may be possible to switch in the "spare" unit from the other FCA which would again restore full operation to the system.

4) ETS converter modules should be mounted directly to SS-type two phase cold plates. This will allow easy integration into the SS thermal control system and allow the FCA systems to operate under very uniform thermal conditions, which will result in increased life expectancy for the components. The heat load should be well within the capability of payload attach points on the IOC SS.

5) Solar array power should be used for back-up power on the DCA. Further study of the circuits necessary to tap power from the tether should be completed. If this technique proves to be too costly or unreliable, solar power should be re-evaluated to provide all of the DCA requirements.

6) Results of the magnetic field study and the orbit perturbations simulations indicate that development of PMG operations scenarios may be very complicated. The equipment required to control the IxB phasing will include; a method to determine end-mass position, velocity and acceleration, measurement or prediction of magnetic field strength and direction, position of the sun (day or night), SS load requirements, and SS excess power available for ETS use.

7) Further simulations and analysis are required to quantify the long term effects of ETS operation on SS orbit parameters, in particular the eccentricity. New methods of analyzing tether systems need to be developed that will speed the analysis of this type of tether effect.

8) Tether repair and replacement appears to present a formidable operational and technical challenge. If robotic repair is contemplated the tether construction must be kept simple. Multi-layer tether designs would make remote repair even more difficult than it already is. However, to meet the requirements of long life, EMI shielding, and micrometeoroid resistance it may be necessary to adopt a multi-layer approach.

A severed tether will present a very difficult challenge. Both ends of the tether must be located and brought together if repair is to be attempted. If a single tether is used the deployed end mass and attached tether end will start drifting immediately. Recovery will have to be completed in a few orbits, otherwise significant OMV fuel will be required to affect the recovery. The broken tether will present an obstacle to the recovery and return operations since its exact position and orientation will not be known. In fact the tether may wrap itself around the end mass complicating or perhaps eliminating the ability of the OMV to dock with it.

A multiple tether approach might help solve some of these problems, but would introduce problems of its own. A multiple tether approach would allow one of the tethers to be severed without losing operation of the ETS or allowing the end mass drifting away. Also, the ends of the tether would be easy to locate by simply tracing the tether from the DCA and the FCA until the end is located. However, a multi-tether design will probably be significantly more expensive to design and build. The tether packaging and deployment operations appear to be much more complex. This design approach should be studied further if a suitable repair scenario is not found for the single tether approach.

9) The recommended baseline ETS is a 100 kW system. This recommendation is less than the reference system (200 kW) because of the availability of components capable of handling the voltage and current levels of the higher power system. The recommended growth approach for the 100 kW system is to parallel two such systems to reach the 200 kW level. Future developments in the areas of solid state components would change this recommendation back to a series system if this could be accomplished.

A series system appears to be superior to a parallel arrangement of converters because of complications in synchronization and reconfiguration of the system in case of a converter failure.

10) The estimated cost of a 100 kW Electrodynamic Tether System is $43M. The non-recurring costs are estimated at $24.4M and the recurring costs are $18.6M ($9.3M per ICA). This estimate represents the costs of designing and building the hardware. Life Cycle Costs (LCC) were not a part of this study, but are obviosly very important to assessing the overall economics of the ETS concept compared to conventional methods of accomplishing the same tasks.

Based on generating capacity the equivalent photovoltaic (PV) system hardware would cost approximately $200M (using $2000/W as a guideline). The ETS hardware costs are very low compared to the PV system. However, the maintenance costs for the two systems will be very different and must be evaluated before a final cost comparison can be made.

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